22

THE PETROGRAPHY, STRUCTURE, AND MODE OF EMPLACEMENT OF THE COBAW GRANITE, VICTORIA

By A. J. Stewart

Department of Geology, Yale University, New Haven,
Connecticut, U.S.A.

Abstract

The Cobaw Granite (Upper Devonian) is a 'high-level', compound granite which has a subrectangular shape and an area of 200 square miles. It consists of four main intrusions (numbered G1 to G4), the later emplaced inside the earlier. G1 is an irregular dyke of hypersthene porphyrite in the north-eastern part of the massif. G2 is a large ring of coarse-grained granite, characterized by a vertically-dipping, planar orientation of perthite phenocrysts, which is parallel to the outer margin of the ring. G3 is the largest intrusion, a virtually massive, medium-grained granodiorite, which crops out entirely inside G2. G4 is a body of porphyritic granodiorite which interrupts the ring of granite G1, and has a transitional contact with G3. Numerous smaller intrusions are present in the central part of the massif, and the country rocks have remained undisturbed during the intrusive history. Emplacement is believed to have begun with the extrusion of a small flow of hypersthene dacite, followed by the intrusion of the granite G2 by minor block stoping of a ring fracture zone, to form a true ring dyke. Because of the large size of the massif, it is thought that these fractures reached the surface, so that restricted flows of rhyolite appeared, accompanied by slight cauldron subsidence. Subsurface fracturing of the central block of country rock allowed underground cauldron subsidence to take place inside G2, possibly of two main blocks, to emplace the granodiorite G3, followed by subsidence of a segment of G2 to form G4. A long period of erosion has entirely removed the roof rocks, including the small amount of early extrusives.

Introduction

The Cobaw Granite is a compound granitic body situated in Central Victoria, between Kyneton, 53 miles NW. of Melbourne, and Tooborac, 58 miles N. of Melbourne (Fig. 1a, 1b). The essential features of this region have been described by Hills (1959), and indicate that the granitic bodies found there are 'high-level' magmatic granites, representative of the 'Plutons' in Read's Granite Series (Read 1949), or of the 'Epizonal plutons' in Buddington's scheme (Buddington 1959). Some of them are directly associated with consanguineous acid volcanic rocks (Fig. 1b), and the area is a typical example of post-orogenic magmatic activity at the subvolcanic and volcanic levels.

The study was undertaken to ascertain the mode of emplacement of the Cobaw Granite. The evidence available, coupled with the generally poor exposures, is insufficient to provide a conclusive demonstration of the emplacement mechanism, but there is enough evidence to allow a hypothesis to be put forward. In this account, the term 'Cobaw Granite' is used to denote the whole massif of granitic rocks, and the four main members in their order of intrusion are referred to as G1, G2, G3, and G4 (Fig. 2). The terminology of Nockolds (1954) has been used for the igneous rocks.

The massif consists essentially of a ring of coarse-grained granite G2, surrounding a core of medium-grained granodiorite G3. A prominent, irregular dyke of hypersthene porphyrite at Tooborac forms the earliest intrusion G1 (Singleton 1949), and a fourth intrusion of granodiorite, G4, breaches the ring of granite and

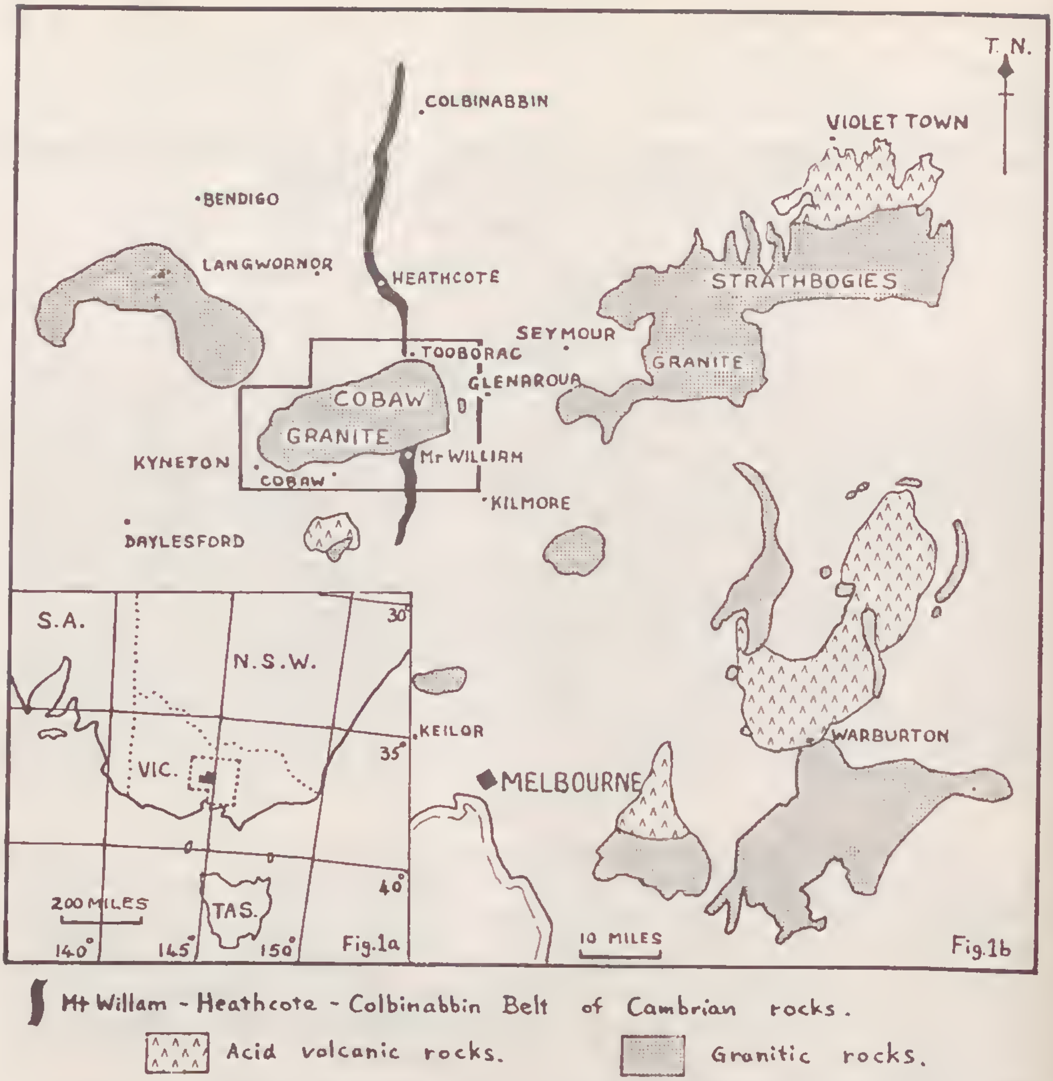


FIG. 1—a. Locality map showing Central Victoria, and the area (in solid black) covered by Fig. 2 (Geological Map of the Cobaw Granite).
b. Map of Central Victoria, showing the Cambrian belt and Upper Devonian igneous rocks. Position of Fig. 2 shown by indented rectangle.

forms the highest part of the area, the Cobaw Ranges. The massif is markedly subrectangular in shape; its long axis measures 24½ miles in an ENE. direction, and the short axis 8½ miles at right angles to this. The total area of all granitic rocks is 210 square miles.

Little work has been done on this granite mass since it was shown on the quarter sheets of the Geological Survey of Victoria, published in the 1860's, and which showed only the outer contact of the granite. The name 'Cobaw Granite' was first used by Edwards (1938). Baker (1942) described the heavy minerals in four

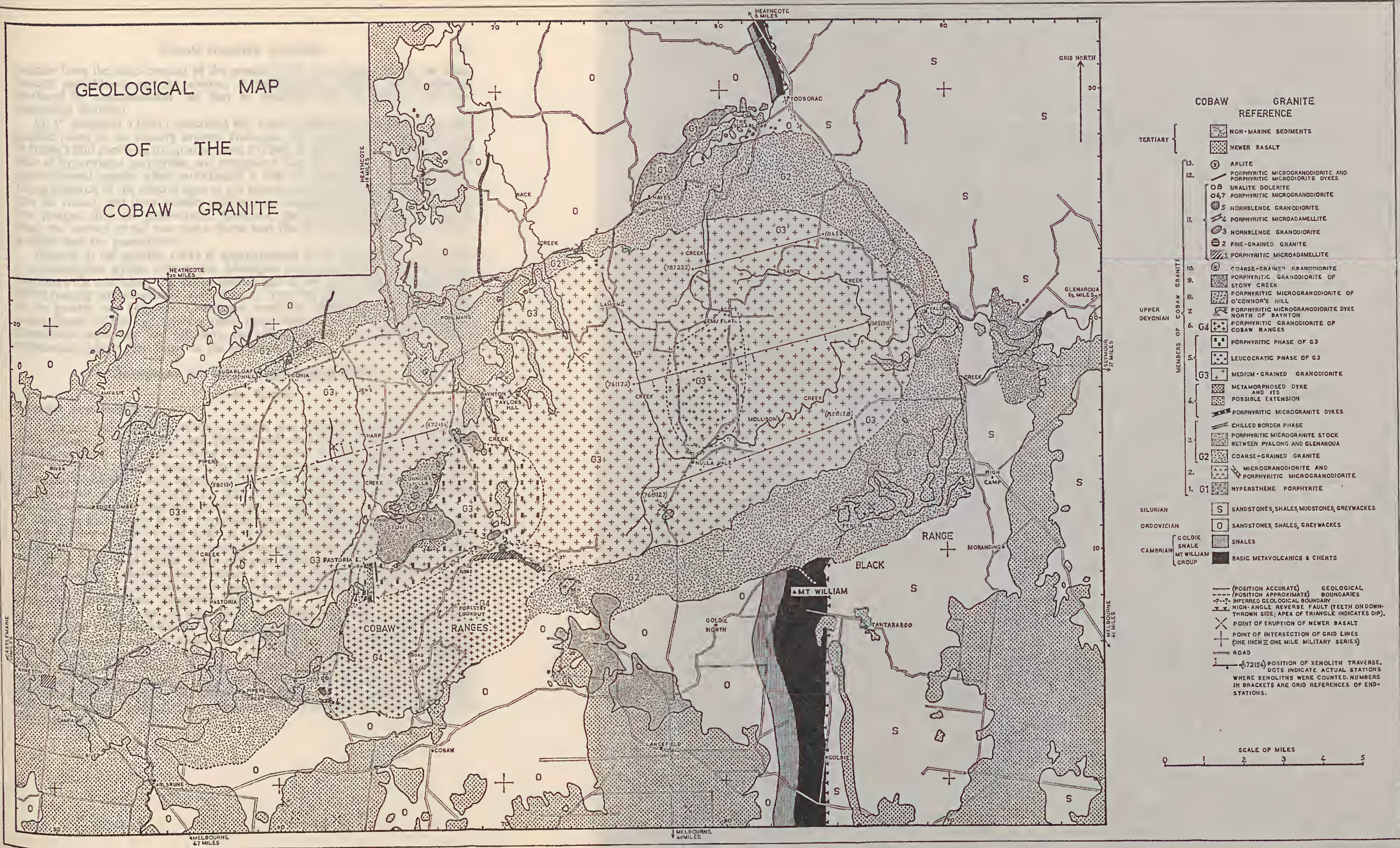

GEOLOGICAL MAP OF THE COBAW GRANITE
COBAW GRANITE REFERENCE
TERTIARY
NON-MARINE SEDIMENTS
NEWER BASALT
UPPER DEVONIAN
MEMBERS OF COBAW GRANITE
13. APLITE
12. PORPHYRITIC MICROGRANODIORITE AND PORPHYRITIC MICRODIORITE DYKES
11.
8 URALITE DOLERITE
6,7 PORPHYRITIC MICROGRANODIORITE
5 HORNBLENDE GRANODIORITE
4 PORPHYRITIC MICROADAMELLITE
3 HORNBLENDE GRANODIORITE
2 FINE-GRAINED GRANITE
1 PORPHYRITIC MICROADAMELLITE
10. COARSE-GRAINED GRANODIORITE
9. PORPHYRITIC GRANODIORITE OF STONY CREEK
8. PORPHYRITIC MICROGRANODIORITE OF O'CONNOR'S HILL
7. PORPHYRITIC MICROGRANODIORITE DYKE NORTH OF BAYNTON
6. G4 PORPHYRITIC GRANODIORITE OF COBAW RANGES
5.
PORPHYRITIC PHASE OF G3
LEUCOCRATIC PHASE OF G3
G3 MEDIUM-GRAINED GRANODIORITE
4.
METAMORPHOSED DYKE AND ITS POSSIBLE EXTENSION
PORPHYRITIC MICROGRANITE DYKES
3.
CHILLED BORDER PHASE
PORPHYRITIC MICROGRANITE STOCK BETWEEN PYALONG AND GLENAROUA
G2 COARSE-GRAINED GRANITE
2. MICROGRANODIORITE AND PORPHYRITIC MICROGRANODIORITE
1. G1 HYPERSTHENE PORPHYRITE
SILURIAN S SANDSTONES, SHALES, MUDSTONES, GREYWACKES
ORDOVICIAN O SANDSTONES, SHALES, GREYWACKES
CAMBRIAN
GOLDIE SHALE SHALES
MT WILLIAM GROUP BASIC METAVOLCANICS & CHERTS
(POSITION ACCURATE) (POSITION APPROXIMATE) GEOLOGICAL BOUNDARIES
-?--?- INFERRED GEOLOGICAL BOUNDARY
HIGH-ANGLE REVERSE FAULT (TEETH ON DOWN-THROWN SIDE; APEX OF TRIANGLE INDICATES DIP).
POINT OF ERUPTION OF NEWER BASALT
POINT OF INTERSECTION OF GRID LINES (ONE INCH ≡ ONE MILE MILITARY SERIES)
ROAD
(672154) POSITION OF XENOLITH TRAVERSE. DOTS INDICATE ACTUAL STATIONS WHERE XENOLITHS WERE COUNTED. NUMBERS IN BRACKETS ARE GRID REFERENCES OF END-STATIONS.
SCALE OF MILES
0 1 2 3 4 5
GRID NORTH
HEATHCOTE 6 MILES
HEATHCOTE 18 MILES
HEATHCOTE 20 MILES
TOOBORAC
THE SUGARLOAF
MC IVOR
HAYES HILL
BACK CREEK
CREEK
SANDY CREEK
LAMBING
EMU FLAT
POHLMAN'S
SUGARLOAF HILL
SIDONIA
JEWS HARP
BAYNTON
TAYLORS HILL
O'CONNORS HILL
STONY CREEK
PASTORIA E.
PASTORIA
PIPERS CREEK
MOLLISON'S CREEK
NULLA VALE
PYALONG
GLENAROUA 1½ MILES
SEYMOUR 17 MILES
MELBOURNE 41 MILES
MELBOURNE 40 MILES
MELBOURNE 47 MILES
CASTLEMAINE
HIGH CAMP
PERCIVALS
BLACK RANGE
MORANDINGS
MT WILLIAM
TANTARABOO
GOLDIE NORTH
GOLDIE
LANCEFIELD
BEN LOCH
COBAW RANGES
FORESTRY LOOKOUT
ROAD
RIDGE
COBAW
ST. BRUNE
KYNETON
CARLSRUHE
REDESDALE
BALD HILL
LANGLEY
AMFASIE
PIPERS
RIVER
(845233)
(787222)
(865199)
(761172)
(858158)
(672154)
(582131)
(769127)
G1
G2
G3
G4
O
S
70
80
90
50
30
20
10

Fig. 2

samples from the outer contact of the granite (G2). The uniformity of the heavy mineral assemblages, and the absence of hydrothermal minerals and of minerals produced by contamination, led him to conclude that the granite had been extensively deroofed.

O. P. Singleton (1949) described the Lower Palaeozoic sediments and later granitic rocks of the country around Tooborac. He found (p. 76) that the rock at Hayes's Hill shown on the quarter sheet 51/SW. as 'gneiss' was a metamorphosed dyke of hypersthene porphyrite, and recognized that the massif possessed a ring of coarse-grained granite which surrounded a core of medium-grained granodiorite. Direct evidence of the relative ages of the granite and granodiorite is lacking in the area he visited, and from indirect evidence he concluded that the ring of granite was younger than the granodiorite. However, direct evidence from other places along the contact of the two rocks shows that this is not so, and that the granite is older than the granodiorite.

Jointing in the granitic rocks is approximately N.-S. and E.-W.; as a result, a subrectangular stream pattern has developed over most of the area. However, Mollison's Ck and Sandy Ck, in the eastern half of the main body of granodiorite, follow roughly arcuate courses some distance from but parallel to the inner margin of the granite ring (Fig. 2). Corestones cover the landscape, and those of the coarse granite of the ring are very much larger than those of the medium-grained granodiorite inside the ring. Similarly, the hills formed on the ring of granite are considerably higher than those on the granodiorite.

Petrography and Relationships of Rock Units

Country Rocks

General Stratigraphy

The rocks into which the Cobaw Granite was intruded consist of folded and faulted Cambrian, Ordovician, and Silurian sediments of the Lachlan Geosyncline (Packham 1960). The trend of the folds and faults is approximately N.-S. The faults bring the Cambrian rocks to the surface, where they form the Mt William-Heathcote-Colbinabbin Belt, separating Ordovician rocks on the western side from Silurian rocks on the east (Fig. 2). The Cobaw Granite transects this belt, and has removed a strip of Cambrian rocks some 12 miles long.

South of the granite, in the Lancefield area, the Cambrian System comprises the Mt William Group, at least 5,000 ft of submarine basic metavolcanics (greenstones) of the spilite-keratophyre association, with minor pyroclastics and cherts, overlain by 2,000 ft of Goldie Shales (Thomas & Singleton 1957). At the surface, the width of the Cambrian belt averages 1½ miles. North of the granite, in the Tooborac area, the Cambrian belt is only ⅝ mile wide, and the volcanic rocks are predominantly tuffaceous (Singleton 1949).

The Ordovician rocks are deep-water sandstones, greywackes, and graptolitic shales. In the Lancefield district they are conformable with the Cambrian rocks, but at Tooborac the junction is faulted. The Silurian sandstones, shales, mudstones, and greywackes occur only to the east of the Cambrian rocks, and are everywhere faulted against them. Though lithologically similar to the Ordovician rocks, they are usually greenish instead of grey, and contain shelly fossils, which indicates shallower-water deposition. The combined thickness of Ordovician and Silurian sediments is about 30,000 ft (from Thomas 1937, Thomas & Singleton 1957, and Packham 1960).

METAMORPHISM

On emplacement of the granite (G2), contact metamorphism affected all the surrounding country rocks, resulting in a ridge of resistant hornfels averaging from ½ to ¾ mile wide. However, at High Camp in the SE. corner, the ridge is 1¼ miles wide and considerably higher than the rest of the aureole, forming the prominent Black Range. Only a very brief petrographic study of the contact metamorphic aureole has been made; fuller descriptions of the thin sections* are recorded in Stewart (1962). An account of the contact metamorphism in the Tooborac area appears in Singleton (1949).

Three specimens of greenstone from Mt William are typical of the metamorphosed Cambrian basic extrusives. TS 8437 has been cut from a specimen from 1,600 yds S. of the granite contact, and consists essentially of oligoclase and actinolite. The larger actinolite crystals have prominent cores of unaltered augite. Other minerals present are abundant ilmenite, chlorite, epidote, clinozoisite, and very rare biotite; hornblende is absent. Faint traces of ophitic texture remain. The mineral assemblage is essentially that of a spilite (Turner & Verhoogen 1960, p. 258), so the rock probably lies outside the contact aureole.

TS 8438, from the peak of Mt William, 1,000 yds from the contact, consists mainly of andesine and hornblende, with some actinolite and rare quartz, augite being absent. TS 8445, from the contact itself, contains oligoclase, hornblende, and quartz; actinolite is absent. This innermost rock is an epidiorite (Hatch, Wells, & Wells 1961, p. 325).

The principal change affecting the Cambrian rocks in the aureole has been the conversion of actinolite to hornblende. The mineral assemblage at the contact belongs to the hornblende-hornfels facies of contact metamorphism, and this extends for 1,200-1,400 yds S. The effect of the granite on the Cambrian rocks in the outer part of the aureole, where the conditions were those of the albite-epidote-hornfels facies (shown by the metamorphosed sediments) was probably very little. This is because the mineralogy of the greenstones was already similar to that of the albite-epidote-hornfels facies, owing to their spilitic character.

A metamorphosed shale from the Goldie Shales at Mt William is a tremolite-biotite-cordierite hornfels (TS 8446), consisting of these minerals with some quartz and abundant ore minerals. The rock is very fine-grained, and the cordierite forms poikiloblasts crowded with inclusions of the other minerals. This rock-type has been recorded only once before in Victoria, from the Tooborac district by Singleton (1949). Most of the contact rocks at Tooborac are tremolite hornfelses.

The Ordovician sediments are typical pelites and psammo-pelites, and have given rise to a variety of contact metamorphic hornfelses. These are:

1. Cordierite hornfels—one type recognized:
    cordierite-muscovite-biotite-quartz hornfels (TS 8465), with occasional small crystals of oligoclase.
2. Biotite hornfels—one type:
    muscovite-biotite-quartz hornfels (TS 8454, 8456), with oligoclase as small crystals and less commonly as larger poikiloblasts.
3. Sericite hornfels—three types:
    (a) biotite-muscovite-sericite-quartz hornfels (TS 8455);

---

* Rock specimens and thin sections (TS) numbers 8203 to 8475 are in the collection of the Geology Department, University of Melbourne.

- (b) muscovite-biotite-quartz-sericite hornfels (TS 8457), a retrograded cordierite hornfels;
- (c) muscovite-quartz-sericite hornfels (TS 8449, 8450, 8451).

The cordierite and biotite hornfelses are not found more than a few yards from the granite. The sericite hornfels forms the major part of the aureole, and is commonly present at the granite contact in association with the cordierite and biotite hornfelses, as well as lying outside them.

The mineral assemblages in the contact metamorphosed Silurian rocks are identical with those in the Ordovician rocks, reflecting the similarity in lithologies. The assemblages noted were cordierite-muscovite-biotite-quartz hornfels (TS 8470, 8472), biotite-muscovite-sericite-quartz hornfels (TS 8473), and muscovite-quartz-sericite hornfels (TS 8468, 8469). Again, the cordierite hornfelses occur only at the granite contact, most of the aureole consisting of the sericite hornfelses.

The mineral assemblages and their distribution in the Ordovician and Silurian rocks indicate a zoned aureole, with an inner zone of biotite hornfels and cordierite hornfels of the hornblende-hornfels facies, and an outer zone of sericite hornfels of the albite-epidote-hornfels facies. Compared with the outer zone, the inner zone is almost everywhere very narrow, ranging from a few inches to a few yards in width. However, where the Cambrian rocks abut against the granite, the zone of the hornblende-hornfels facies is wider, of the order of 1,000 yds, both at Mt William and at Tooborac (Singleton 1949, p. 86-87). This results either from the presence of granite close to the surface, or from the greater reactivity of the greenstones compared to the sediments. At High Camp, the Black Range consists of spotted cordierite hornfels, so that the inner zone is a mile wide.

The narrowness of the inner zone shows that the bulk of the contact metamorphism took place under conditions of the lowest grade of temperature and pressure, the conditions of the albite-epidote-hornfels facies. A high level of emplacement in the crust is therefore indicated.

INTRUSIVE ROCKS

The Cobaw Granite has one large ring of coarse-grained granite G2, with a weakly developed, concentric, platy flow structure, surrounding a younger body of massive, medium-grained granodiorite G3 (Fig. 2). The ring has been breached by a later intrusion G4, but almost certainly it originally covered a full 360°. In all there are 13 members of the massif. Four small igneous bodies are situated outside the granite ring, apart from microgranite dykes; all the other members crop out inside the ring. No cone sheets have been found.

The order of intrusion, as far as can be deduced from field relationships and petrographic similarities, is:

1. Hypersthene porphyrite dyke G1, at Tooborac.
2. Microgranodiorite at Tooborac, porphyritic microgranodiorite at Mt William, and porphyritic microgranite SE. of Tooborac.
3. Granite G2, and porphyritic microgranite between Pyalong and Glenaroua.
4. Porphyritic microgranite dykes.
5. Granodiorite G3.
6. Porphyritic granodiorite G4, of the Cobaw Ranges.
7. Porphyritic microgranodiorite dyke 3 miles N. of Baynton.
8. Porphyritic microgranodiorite of O'Connor's Hill, with a small off-shoot ½ mile to the NE.

(9) Porphyritic granodiorite of Stony Ck, with a small off-shoot 2 miles to the NE.
(10) Coarse-grained granodiorite plug 1 mile SW. of Baynton.
(11) Eight minor intrusions near the boundary of G4.
(12) Porphyritic microgranodiorite and porphyritic microdiorite dykes in the W. part of the massif.
(13) Aplite, pegmatite, and reef quartz.

The evidence of the relative age of each intrusion is discussed individually. Petrographic descriptions are summarized in Tables 1-6.

(1) HYPERSTHENE PORPHYRITE DYKE G1 (summarized from Singleton 1949)

This irregular dyke crops out W. of Tooborac, and is 4 miles long and up to ¾ mile wide; its area is 1·5 square miles (Fig. 2). The trend of the dyke is arcuate, and the curvature is nearly parallel to the arcuate boundary of the granite to the south. There are several smaller bodies at the E. end, and many small dykes and plugs of porphyrite are present between the main dyke and the granite.

The dyke has been metamorphosed by the granite (G2). The least altered rock, farthest from the granite, is a hypersthene porphyrite—see Table 1, Pt 1. Approaching the granite, the rock lightens in colour and a schistosity appears. Nearest the granite contact, the rock is thoroughly schistose, and local granitization of the schist has occurred in a few places.

Only xenoliths of sedimentary origin have been found in the dyke. As the other intrusions in the Tooborac area contain xenoliths of metamorphosed porphyrite derived from the dyke, it is most probable that the hypersthene porphyrite is the earliest intrusion. Its own metamorphic effects are negligible.

(2) (i) MICROGRANODIORITE AT TOOBORAC

This is a small, irregular mass, 1,000 yds long and up to 250 yds wide, which crops out at the eastern end of the hypersthene porphyrite G1, just W. of Tooborac (Fig. 2). Its composition is given in Table 1, Pt 2. Rare xenoliths include sedimentary rocks and metamorphosed hypersthene porphyrite, indicating that the microgranodiorite is younger than G1. The western end of the microgranodiorite is invaded by a medium-grained off-shoot of the granite G2 (Singleton 1949, Fig. 3 and p. 94), and this indicates that the microgranodiorite is older than G2.

(ii) PORPHYRITIC MICROGRANODIORITE AT MT WILLIAM

This rock is similar to the microgranodiorite at Tooborac, except for its porphyritic texture—see Table 1, Pt 3. The dyke is 1,600 yds long, and strikes southeasterly away from the granite (G2) into the greenstones of Mt William (Fig. 2). The biotite flakes show a faint planar parallelism, and the dyke carries small xenoliths of greenstone. A few 1-inch lenticles of quartz are also present, aligned parallel to the biotite flakes. The dyke is similar in texture to the slightly metamorphosed parts of the hypersthene porphyrite dyke at Tooborac, indicating that some recrystallization took place during the intrusion of G2. Hence, this dyke is older than the granite, and possibly contemporaneous with the microgranodiorite at Tooborac.

(iii) PORPHYRITIC MICROGRANITE 3 MILES SE. OF TOOBORAC

At this locality, at the contact of the granite G2, and the country rock, the granite intruded between closely jointed blocks of a white, fine-grained, porphyritic

TABLE 1

Dyke rocks intruded before granite, G2, of ring

ROCK	TEXTURE	MINERAL CONTENT	REMARKS
ART 1 yperathene porphyrite, G1 (from Singleton, 1949).	Phenocrysts up to 5 mm across ln fine-grained groundmaas.	Phenocrysts: Quartz (rare); Calcic andesine; strongly zoned from An_{50} (core) to An_{40}; commonly veined and rimmed with oligoclase, An_{20}; Biotite: Hypersthene Secondsries: Chlorite (after biotite); Muscovite (possibly after plagioclase). Groundmaas: Quartz, Orthoclase, Plagioclase, Biotite (pale yellow). Accessories: llmenito, Apatite, Zircon, Pyrlte (rare).	Biotite phenocrysts are generally secondary sfter ilmenite, but a minor modification bas primsry biotite phenocryats and no hypersihene. Hypersthene ls usually rlmmed by secondsry biotite, limenite, and rare green hornbiende.
ontact metamorphosed ypersthene porphyrite; tage 1.	Spotted appesrsnce, fine-grained groundmsss.	Phenocrysts: Andesine; zoned from An_{40} (core) to An_{35}, in aggregstes; oligoclase rims (An_{20}) sre wider; commonly sssocisted with clots of biotite; Biotite (primary) Secondaries: A brown, isotropic msterlal is present in the corce of plagioclase crystale; some have muscovite flakes associated. Groundmass: Quartz and feldepar intergrowths; Biotite. Accessory: Iron ore (disseminsted through groundmsss).	Hyperathene is completely replaced by clota of yellow to dark brown biotite; spatite, ilmenite, and rsre green hornblende are associated.
tage 2	Lighter grey colour; fine-grained groundmasa is echistose or granoblastic.	Phenocrysts: Sodic andesine (core, An_{35}) zoned to calcic oligoclase (An_{25}), in sggregates; oligoclsse rims(An_{20}) are wider; qusrtz is associated; Biotite (clots). Groundmass: Intergrowths of quartz, orthoclase, and oligoclase; Biotite.	Clots of biotite (after hypersthene) are more scattered, flakes are larger; small amounts of green hornbiende, apatite, and sphene are associsted, but no Ilmenite.
tage 3.	Fine-grained groundmsss, schistose or granoblsatic.	Blastophenocrysts (or Porphyroblasts): Jacketed plagioclase; cores are zoned from sodic andesine (An_{35}) to calcic oligoclase (An_{30}); oligoclase rims sre An_{20}; Biotite (redder than in stages 1 and 2). Groundmass: Qusrtz, orthoclase, oligoclase, Biotite. Accessories: Ilmenite, Apaiite, Zircon, Tourmaline, Hornblende.	Large garnets are present in one thin section from Hayes' Hill.
PART 2 icrogranodiorite at Tooborac (from Singleton, 1949)	Fine-grained, has a few phenocryste up to 12 mm acroas.	Phenocrysts: Hornblende; prismatic, not abundant. Groundmsss: Quartz; Orthoclase; plagioclase, zoned from calcic andeeine (core, An_{45}) to sodic oligoclase (An_{15}); Biotite; Hornblende Accessories: Iron ore, Zircon, Apatite, Sphene, Allanite Secondaries: Rare aggregstee of colourless, fibroue amphibole are poasibly after pyroxene.	Some ioteratitisl biebe of myrmekite and a few large poikiliths of orthoclaee are present. Modal Compoeition: Quartz 16% Orthoclase 11 Plagioclase 50 Biotite 20 Hornblende 3 100 Acceasories 0.1%
PART 3 orphyritic microgranodiorite at Mt William (T.S. 8367)	Phenocrysts up to 4 mm across in fine-grained groundmsss.	Phenocrysts: Quartz; Andesine (aggregates of seversl individuals); Biotite. Secondaries: Chlorite (after biotite); Sericite (after plsgioclase) Groundmass: Quartz; Orthoclase; Biotite. Accessories: Zircon, Hematite, Apatite, Magnetite.	Slightly metamorphosed.
PART 4 Metamorphosed porphyritic microgranite (T.S. 5374).	Blaatoporphyritic, fine-grained groundmsas.	Blaatophenocrysts: Quartz (anhedrsl, and deeply embayed); Orthoclase (anhedral); Oligoclase (anhedral). Groundmass: Quartz; Orthoclase; Biotite (rsre); Muscovite. Accessory: Ilmenite.	Groundmass hsa patches of different grain-size.

microgranite. The rock has been thoroughly recrystallized (see Table 1, Pt 4), and must be earlier than G2.

(3) (i) GRANITE G2

This is the second-largest intrusion in the Cobaw Granite; its exposed area is 61·7 square miles. It forms a nearly complete ring around the granodiorite G3, and varies in width from a minimum of 400 yds N. of Baynton to a maximum of 2·8 miles at High Camp and Piper's Ck. The average width is 1·2 miles. The western contact with the country rock is concealed beneath Tertiary basalt, so here the ring appears narrower. North of Cobaw, the granite ring is interrupted by the porphyritic granodiorite G4, of the Cobaw Ranges (Fig. 2). However, as the granodiorite carries xenoliths of granite, and also large perthite phenocrysts, it seems very probable that the granite originally extended through this area, and was breached by G4.

Exposures of fresh granite are rare. Near Kyneton, the granite is pale grey and porphyritic, with 1" phenocrysts of perthite set up to 2" apart in a grey, medium-grained matrix. Near High Camp, the rock is bluish grey and not notably porphyritic, though its grain-size is uneven. The weathered granite seen elsewhere is a coarse-grained, quartz-rich rock, in which perthite phenocrysts are abundant. Good exposures of the granite are found in Mollison's Ck at Pyalong, and in the creek ¾ mile E. of Sugarloaf Hill, Sidonia.

The petrographic description of the granite is set out in Table 2, Pt 1. The ratio of K-felspar to plagioclase places the rock among the calc-alkaline granites of Nockolds (1954).

TABLE 2

Granite, G2, and dyke rocks intruded before granodiorite, G3

ROCK	TEXTURE	MINERAL CONTENT	REMARKS
PART 1 Granite of ring, G2 (calc-alkaline granite, T.S. 8327-8346 incl.).	Phenocrysts up to 25mm long, in coarse-grained groundmass.	Phenocrysts: Perthite; Carlsbad twinning is common. Groundmass: Quartz (contains innumerable, minute, irregular inclusions); Perthite (exsolved plagioclase is An_{09}, calcic albite); usually carlsbad twinned; Sodic andesine, An_{32}; where zoned, cores are middle andesine, An_{42}, and rims are calcic oligoclase, An_{26}. Biotite; X=pale straw yellow, Y=Z=deep red-brown; usually in aggregates Accessories: Zircon, Apatite, Magnetite, Allanite, Hematite, Muscovite (primary), Garnet, Hornblende, Rutile, Monazite. Secondaries: Kaolin (after orthoclase); Sericite (after plagioclase); Chlorite and rare sphene (after biotite); Muscovite (after both feldspars); Limonite staining.	Muscovite is present in two 1. Large, anhedral crystals with cleavage well shown; regard primary. 2. Complex, irregular webs, or crystals, or groups of small in feldspar; regarded as secon Sericite has formed in the core plagioclase crystals. Modal Composition: granite of Too area, from Singleton (1949, corrected to 100%. Quartz 43% Perthite 32 Plagioclase 18 Biotite 7 100 Accessories
PART 2 Porphyritic microgranite (chilled border phase, T.S. 8368-8371, incl.).	Glomerophenocrysts in fine-grained, allotriomorphic groundmass.	Phenocrysts: Quartz, Orthoclase, Oligoclase, Biotite. Groundmass: Quartz, Orthoclase, Oligoclase, Biotite, Muscovite. Accessory: Magnetite.	Phenocrysts are absent from the mic granite east of Back Creek.
PART 3 Porphyritic microgranite between Pyalong and Glenarous (T.S. 8475).	Phenocrysts up to 5 mm across in fine-grained groundmass.	Phenocrysts: Quartz, Orthoclase, Oligoclase, Biotite Groundmass: Quartz, Orthoclase, Oligoclase, Biotite Accessories: Muscovite, Magnetite, Zircon, Apatite. Secondaries: Chlorite (after biotite).	
PART 4 Porphyritic microgranite dykes: 1. Most easterly dyke (T.S. 8372).	Phenocrysts up to 6 mm across in fine-grained groundmass.	Phenocrysts: Quartz (bipyramidal), Orthoclase, Oligoclase. Groundmass: Quartz, Orthoclase, Oligoclase, Biotite, Muscovite. Accessories: Garnet, Topaz, Zircon. Secondaries: Limonite, Chlorite.	Biotite has been largely replaced chlorite.
2. Spherulitic granophyre on north bank of Jew's Harp Creek (T.S. 8373).	Partly porphyritic (see remarks).	Phenocrysts: Quartz (rounded and embayed); Orthoclase (abundant, forms spherulites); Andesine (sericitized); Biotite (green, not common). Secondaries: Chlorite, Leucoxene, Sericite. Groundmass: Quartz, Orthoclase, Muscovite. Accessories: Zircon, Apatite, Calcite.	Chlorite pseudomorphs after biotite pyroxene phenocrysts are common. Calcite is present as discrete cryst Groundmass is subordinate to ph crysts and spherulites, and forms discrete patches.

The country rocks in general are undisturbed right up to the granite, and the contact of the two rocks is sharp and transgressive, except where local felspathization has occurred in McIvor Ck at Tooborac (Pl. 32, fig. 1). In this area, veining of the country rock by the granite is sufficiently extensive to resemble a 'stockwerk'

(Singleton 1949). In Mollison's Ck at Pyalong, a small granite tongue intrudes the Silurian sediments parallel to the strike, and sends a number of veins of pegmatitic granite into joints and along bedding planes.

Xenoliths are present throughout the granite, but are not plentiful. They are described later in the section on xenoliths.

The granite has been little affected by the later granodiorite G3, but W. of Ben Loch, close to G4, the granite G2 is much finer-grained than normal, and has an aplitic appearance. In thin section (TS 8350), the rock is seen to be porphyritic, with phenocrysts of quartz, orthoclase, oligoclase, and biotite, in an aplitic groundmass of the same minerals. Unlike the biotite phenocrysts in the chilled border phase (Table 2, Pt 2) the prism faces of the biotite crystals are wispy and shredded, and this suggests that heating has occurred, for biotite is the first mineral in a granite to show effects of thermal metamorphism (Harker 1939, p. 114).

The ring of granite G2 is older than the granodiorite G3, on the direct evidence of dykes of granodiorite and porphyritic microgranodiorite of G3 which invade the granite, particularly at Sugarloaf Hill, Sidonia (Fig. 2, and Pl. 32, fig. 2); these are described later. Other reasons are given in the section on G3.

(ii) CHILLED BORDER PHASE

This rock is found in patches along the northern contact of the granite with the country rock, and consists generally of porphyritic microgranite (Table 2, Pt 2). Microgranite extends for ¾ mile along the outer contact E. of Back Ck (Fig. 2), but generally the chilled border phase forms a body only a few yards in extent.

(iii) LARGE DYKE WEST OF TOOBORAC

Described and mapped by Singleton (1949), this dyke is similar to the granite of the ring, but is medium-grained and equigranular, and has no flow structure visible. There are three off-shoots at the eastern end, and many smaller scattered plugs are also present here (Fig. 2).

(iv) PORPHYRITIC MICROGRANITE BETWEEN PYALONG AND GLENAROUA

This stock is roughly rectangular (Fig. 2); its length is 2·9 miles, its width 1 mile, and the area 2·6 square miles. The composition of the body is shown in Table 2, Pt 3. The microgranite contains very few xenoliths, and its contact metamorphic effects have not been sufficient to produce a resistant ridge, although the northern boundary of the stock is exposed along the southern end of a prominent range of hills, which extends for 3½ miles to the north. Aplite in masses several yards across is present along the northern margin of the microgranite.

(4) (i) PORPHYRITIC MICROGRANITE DYKES

Five dykes of porphyritic microgranite strike N. for various distances from the northern boundary of the granite. These are the 'elvan dykes' shown on the quarter sheets 51/SW. and 13/SE. The petrography of the dykes is given in Table 2, Pt 4. The most easterly dyke, which strikes N. for 3¼ miles and is about 100 yds wide, carries bipyramidal quartz, and some garnet and topaz; the longest dyke also contains bipyramidal phenocrysts of quartz. The dyke on the N. bank of Jew's Harp Ck is an excellent example of a spherulitic granophyre, and contains a few euhedral crystals of calcite.

(ii) METAMORPHOSED DYKES

Some apparently normal dyke rocks proved on thin sectioning to have a metamorphic texture, exactly as in the xenoliths in G2 and G3; small crystals of ferromagnesian minerals are subidioblastic, and the small felspar grains are idioblastic. Large poikiloblasts of quartz and plagioclase are common.

In a typical example from 2½ miles NNE. of Piper's Ck (TS 8383, 8384), it is difficult to tell which of the large crystals of quartz and plagioclase may be porphyroblasts, and which blastophenocrysts. Crenulate margins are present between the crystals and the undisturbed groundmass, and this indicates an origin by replacement. Other crystals have clearly pushed aside the small surrounding grains, so that the rock was softened at some stage.

Another example, 2 miles NW. of Piper's Ck, forms a patch of small, fine-grained boulders at the contact of G2 and G3. The thin sections (TS 8385, 8386) show a small sedimentary xenolith included in the metamorphosed porphyritic microgranodiorite. On the Ridge Rd in the Cobaw Ranges, 2½ miles WNW. of Ben Loch, a group of large boulders, with steep W.-dipping joints, is composed of metamorphosed microgranodiorite (TS 8387), which carries small basic xenoliths.

Four exposures of metamorphosed dyke rocks were found in the granodiorite G3, along the S. margin of the porphyritic granodiorite of Stony Ck. The exposures form a strip which strikes NE. for 2 miles (Fig. 2). The rocks are hornblende-bearing (TS 8388-8390 incl.), and so the four exposures are probably the remains of a large dyke, and not a resistant bed of sedimentary country rock, as hornblende is absent from the normal sedimentary xenoliths, and from the hornfelses in the contact aureole. In addition, the most westerly outcrop itself carries a 'second-cycle' xenolith.

These metamorphosed dyke rocks are apparently rafts and large xenoliths in G3 and G4, and so are older than these bodies.

(5) (i) GRANODIORITE G3

This rock forms the bulk of the Cobaw Granite, and crops out within the ring of granite G2. The whole mass of granodiorite has a subrectangular shape, and the ends are almost perfectly semicircular (Fig. 2). It has an area of 127 square miles, excluding the areas of the intrusions at Stony Ck and O'Connor's Hill.

The typical granodiorite is a handsome, medium-grained, speckled rock. Fresh specimens are pale bluish grey, and slight variations in grain-size are ubiquitous. The rock is described in Table 3, Pt 1. Xenoliths are plentiful throughout the granodiorite, and are discussed later in the section on xenoliths.

An adamellite phase is present in the centre of the eastern half of the granodiorite (Fig. 2, Table 3, Pt 2). The adamellite is more leucocratic than the granodiorite, and contains 70% felspar and 6% ferromagnesians against 52% and 10% for the typical granodiorite. Otherwise the mineralogy is the same as that of the granodiorite, the grain-size is only slightly finer, and xenoliths in the adamellite are as numerous as in the main body of the granodiorite. No contact between the two rock-types was ever seen in the field. Similar occurrences have been reported by Pitcher (1953), and mentioned by Balk (1937, p. 67-68).

The granodiorite E. of O'Connor's Hill and N. of the Cobaw Ranges is coarser-grained than the typical granodiorite G3, and also carries 12 mm phenocrysts of plagioclase and some of perthite. No boundary with the main granodiorite was found; there was merely a gradual decrease of the phenocrysts away from this area, suggesting that this phase is similar in its occurrence to the adamellite phase. The

TABLE 3

Granodiorite, G3, and granodiorite of Cobaw Ranges, G4

ROCK	TEXTURE	MINERAL CONTENT			REMARKS
T 1 odiorite, G3 (main rt of massif, inside g of granite, G2; .S. 8203-8240 incl.). Modal Composition: Quartz 38% Microperthite 17 Andesine 35 Biotite 9 Hornblende 1 100 Others 0.2 Total feldspar = 52%, Total ferromagnesians = 10%.	Medium-grained, equigranular, hypidiomorphic	Essentials: Quartz; contains innumerable tiny, irregular inclusions, and some needles of ?rutile. Biotite; two pleochronic varieties are present: 1. X=pale straw yellow, Y=Z=dark greenish brown (western half of G3); 2. X=pale brownish yellow, Y=Z=dark reddish brown (eastern half of G3). Accessories: Zircon, Apatite, Allanite, Magnetite, Ilmenite, Hematite, Sphene, Augite, Garnet, Epidote, Clinozoisite, Pyrite, Chalcopyrite.	microperthite; Carlsbad twinning is rare: accompanied by microcline in a few thin sections, but this is uncommon. Hornblende; prisms up to 7mm long; generally X=pale yellow-green Y=olive green, Z=dark green; in some thin sections, X=greenish brown, Y=reddish brown, Z=red brown.	Middle andesine, An_{38}; where zoned, cores are calcic andesine (An_{44}), and rims are calcic oligoclase (An_{30}). Some oscillatory zoning present, and also jacketing of andesine by more sodic plagioclase. Secondaries: Chlorite and sphene (after biotite), Sericite (after plagioclase), Kaolin (after orthoclase), Tremolite and actinolite (after pyroxene), Calcite, Muscovite, Limonite.	Some micrographic intergrowth of quartz and orthoclase is present in a few thin sections. Allanite crystals reach 2mm in length, and fresh specimens show concentric zoning. Primary sphene is anhedral, and appears to be a late-stage mineral. Augite is found only as remnants inside aggregates of tremolite and actinolite. Garnet is colourless and unaltered. Pyrite is always rimmed with hematite. Sericite is found in every thin section, and has formed in the most calcic parts of the plagioclase crystals. Chlorite is very common after biotite, and is almost invariably accompanied by grains of sphene in strings along the cleavage of the original biotite. Calcite forms discrete crystals in some thin sections. Uralitic aggregates after pyroxene have cores of colourless tremolite, surrounded by green actinolite, and rimmed with dark green hornblende.
PART 2 amellite phase in astern half of granoiorite G3 (T.S. 8241-8244 incl.).	Medium-grained, equigranular.	As for granodiorite G3 (see above).			Modal Composition (average of T.S. 8243 and 8244): Quartz 24% Microperthite 29 Andesine 41 Biotite 6 100 Hornblende 0.1 Others 0.2 Total feldspar = 70%, Total ferromagnesians = 6%
PART 3 rphyritic granodiorite, G4, of the Cobaw Ranges, (T.S. 8278-8299 incl., and 8321).	Phenocrysts up to 40 mm long in medium to coarse-grained groundmass.	Phenocrysts: Quartz (up to 5mm across); Groundmass: Quartz, Orthoclase, Andesine, Biotite, Hornblende Accessories: Zircon, Apatite, Augite, Sphene, Allanite, Magnetite, Ilmenite, Epidote, Hematite, Pyrite.	Perthite (up to 40 mm long); exsolved plagioclase is albite An_{08}; generally Carlsbad twinned.	Andesine: Biotite (rare); Hornblende (rare). Secondaries: Chlorite and sphene (after biotite), sericite (after plagioclase), Kaolin (after orthoclase), Muscovite	Augite is replaced directly by hornblende, (in contrast to G3). Modal Composition (average of T.S. 8290 and 8321): Quartz 34% Orthoclase 22 Andesine 35 Biotite 8 Hornblende 1 100 Others 0.3 This analysis excludes the large perthite phenocrysts.
PART 4 Granodiorite border phase of G4 (T.S. 8300-8309 incl.).	Medium-grained, equigranular.	Essentials: Quartz, Orthoclase, Andesine, Biotite. Accessories: As for G4 (above), plus Hornblende.		Secondaries: As for G4 (above).	Modal Composition (average of T.S. 8305 and 8306): Quartz 33% Orthoclase 24 Andesine 37 Biotite 6 100 Hornblende 0.3% Others 0.1%

coarser granodiorite (TS 8326) has less perthite and more andesine than the typical granodiorite, otherwise the rocks are similar. The phenocrysts and xenoliths have a vertical planar orientation at one locality (Fig. 8).

Dykes of Granodiorite G3 which intrude the Granite G2

There are at least two of these dykes; the larger one at Sidonia (Fig. 2) extends for 1½ miles E. from Sugarloaf Hill, and the smaller dyke, situated 4¼ miles NE. of Baynton and 1 mile E. of Back Ck, is ½ mile long. Both dykes are parallel to the contact of G3 with G2.

The dyke at Sidonia provides the best evidence that the granodiorite G3 intrudes the ring of granite G2, and hence is younger. The western half of the dyke is identical with the typical granodiorite G3, both in hand-specimen and in thin section. East of Sugarloaf Hill, the dyke divides into two parallel branches, and a third, smaller off-shoot trends S. Several excellent exposures of the contacts of the granite and the granodiorite can be seen in the creek ¾ mile E. of the hill (Pl. 33; and Pl. 34, fig. 1), and both branches dip at 45° S. towards the main granodiorite. Xenoliths of granite are present in the granodiorite, and there are many places where the granodiorite of the S.-trending off-shoot transects the E.-W. planar orientation of the perthite phenocrysts in the granite (see below).

E. of the creek, the N. branch of the granodiorite dyke is very narrow, and has branches and anabranches a few feet across. These contain many granite xenoliths and xenocrysts of perthite derived from the granite.

The bulk of the dyke is similar to typical granodiorite G3 both in texture and mineralogy—i.e. it consists of quartz, andesine, orthoclase, and biotite, and the usual accessories (TS 8258, 8259). Towards the eastern end, hornblende is absent, and the rock is porphyritic and very similar to the much smaller dyke which intrudes the granite 3 miles N. of Baynton (described below). The biotite flakes have a planar orientation which is parallel to the margins of the dyke.

The other tongue of granodiorite, 4¼ miles NE. of Baynton, is much smaller and not nearly as well exposed. It lacks hornblende, but otherwise is typical medium-grained granodiorite (TS 8261-8263).

Several dykes of porphyritic microgranodiorite, which are directly connected with the main granodiorite body, intrude the granite at a locality 1¼ miles SW. of Hayes's Hill. The dykes are 3 or 4 ft wide, and contain xenoliths of granite and country rock. These dykes cut across the planar structure of the granite, and the biotite flakes in the microgranodiorite have a planar orientation of their own, parallel to the walls of the dykes. The dykes have aplitic edges, and are somewhat heterogeneous; they contain biotite-rich schlieren, coarse patches, fine patches, and non-porphyritic patches. Small irregular veins of microgranodiorite have been injected into the granite.

In general, the contact of G3 with G2 is concealed, but where exposed it is sharp and distinct. The contact surface is smooth and even, but seldom maintains a constant direction for more than a few feet. Apophyses of granodiorite invade the granite in many places, and in these the rock is commonly porphyritic. A vein of aplite up to 1" wide occurs between the granite and the granodiorite, but it is usually associated with the smaller apophyses rather than with the main contact of the two rocks. A similar feature has been noted by Pitcher (1953) in the Rosses granitic complex.

The granodiorite G3 is younger than the granite G2 for the following reasons:

(i) At Sidonia, a large forked dyke of granodiorite G3 intrudes G2 (Fig. 2); it contains xenoliths of granite (Pl. 34, fig. 1), and has a platy flow structure parallel to the contacts with the granite. A S.-trending off-shoot of this dyke cuts cleanly across the planar structure in the granite.

(ii) At many other localities along the contact of G2 and G3, the granodiorite cuts across the planar structure of the granite.

(iii) Near the contact SW. of Hayes's Hill, three detached blocks of granite, each measuring several yards across, are enclosed in the granodiorite (Fig. 2). The largest appears to have moved only a short distance from its original position, as it fits into a corresponding embayment in the main body of the granite.

(6) Porphyritic Granodiorite of the Cobaw Ranges G4

This intrusion, which crops out N. of Cobaw, has an area of about 15 square miles, and is elongated parallel to the main axis of the Cobaw Granite (Fig. 2). It interrupts the southern part of the granite ring for 6 miles. Owing to dense forest cover, the only fresh exposures are provided by recently blasted boulders along the Ridge Rd.

The granodiorite is medium to coarse-grained, and in contrast to the speckled blue-grey granodiorite G3, fresh specimens are a smoky blue-green, and contain large salmon-pink phenocrysts of perthite, ranging from 15 mm to 40 mm long. Smaller phenocrysts of quartz and plagioclase are up to 5 mm across (Table 3, Pt 3). The perthite phenocrysts are abundant in some places and fewer in others. They appear to be particularly common and at their largest in the middle of the intrusion. Small microgranodiorite dykes, about 2″ wide, cut the granodiorite at one or two localities. The dykes have transitional margins with the host rock, and in places are accompanied by basic schlieren and elongate masses of pegmatite 1 to 2 ft across.

The contact between G4 and the Ordovician country rock is sharp and transgressive, and the sediments are undisturbed. The eastern junction of G4 and the granite G2 is similarly cross-cutting; the western junction is not exposed. However, the contact of G4 and the granodiorite G3 is a zone of transition some hundreds of yards wide.

Along the southern and eastern margins of G4, the granodiorite is non-porphyritic; both the large perthite crystals and the smaller quartz and plagioclase phenocrysts are absent, and the rock is evenly medium-grained. Otherwise, the granodiorite has the same mineralogy and mode (Table 3, Pt 4) as the bulk of the intrusion, and the reason for the absence of phenocrysts is not fully understood. However, the slightly greater abundance of the large perthite phenocrysts in the centre of the intrusion, in line with the ring of granite G2, indicates that they may be xenocrysts derived from the granite, and their large size suggests that some assimilation of the granite G2 by the granodiorite G4 occurred. Their numbers could then be expected to lessen away from the region of assimilation, and this is found to be the case.

Rare xenoliths in G4 are of two types: coarse-grained granite, and medium to coarse-grained 'dioritic' rock. The first type are identical in appearance with the granite G2 of the ring, and must have been stoped off during the intrusion of G4. The second type have a very pale speckled appearance, and consist essentially of orthoclase and andesine, the latter much sericitized (TS 8416). The other minerals present are mainly quartz, biotite (almost completely altered to chlorite and sphene), and hornblende (practically unaltered). The origin of these xenoliths is not known.

As G4 has a transitional contact with G3, it must have been emplaced soon after the latter, and before the granodiorites of O'Connor's Hill and Stony Ck, as these have much sharper contacts with G3.

(7) Porphyritic Microgranodiorite Dyke N. of Baynton

This dyke, which may be a direct and contemporaneous off-shoot from the granodiorite G3, crops out 3 miles N. of Baynton. It is 970 yds long, and three small isolated outcrops of the same rock-type are exposed within 600 yds of the eastern end (Fig. 3). The rock is pale grey, of medium to fine grain, and porphyritic. Specimens taken at intervals from W. to E. along both branches of the dyke (Table 4, Pt 1) show a relative increase towards the east in the content of silicon

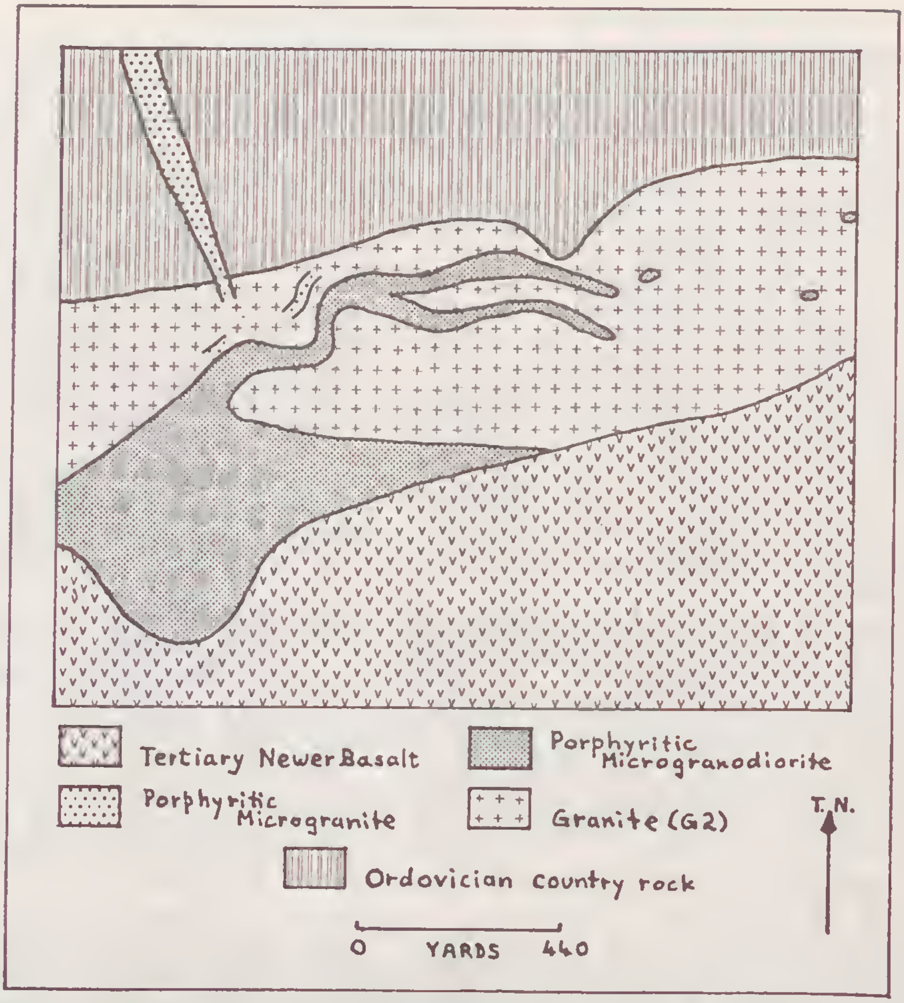


Fig. 3—Geological map of the porphyritic microgranodiorite dyke situated 3 miles N. of Baynton.

and sodium. The contacts of the dyke with the granite G2 are sharp, and thin layers of aplite are commonly present between the two rock-types. Occasional xenoliths of granite are present. The rock contains no hornblende, and is similar to the rock at the eastern end of the granodiorite dyke at Sidonia, which contains hornblende in its western part but none in the east.

One of the isolated exposures E. of the main dyke is of interest, as here the porphyritic microgranodiorite clearly filled a fissure formed by the displacement of blocks of granite along joint planes. The biotite flakes of the microgranodiorite show a strong platy flow structure parallel to the walls of the fissure.

(8) Porphyritic Microgranodiorite of O'Connor's Hill

This body, which forms a group of prominent hills, crops out over an area of 1·2 square miles in the middle of G3 (Fig. 2), and a small off-shoot lies ½ mile to

TABLE 4

Minor intrusions emplaced after G4, mostly in central part of massif

ROCK	TEXTURE	MINERAL CONTENT		REMARKS
PART 1 Porphyritic microgranodiorite dyke north of Baynton (total continuous length = 970 yards; T.S. 8264-8271 incl.).	Phenocrysts up to 5 mm across in fine-grained groundmass.	Western end of dyke, T.S. 8264: Phenocrysts: Quartz, Andesine, Biotite Accessories: Zircon, Apatite, Ilmenite, Garnet.	Groundmass: Quartz, Orthoclase, Andesine, Biotite. Secondaries: Chlorite, Sphene, Sericite,	Proportion of phenocrysts in total rock lessens from west to east, Modal Composition: 1. Rock at western end of dyke (T.S. 8264). — 2, Rock 660 yards to the east (T.S. 8268),
		440 yards to the east, T.S. 8265, 8266: Phenocrysts: Quartz, Orthoclase, Andesine, Biotite Accessories: As above, plus allanite.	Groundmass: Quartz, Orthoclase, Andesine, Biotite. Secondaries: As above.	Quartz 24% — Quartz 40% Orthoclase 15 — Orthoclase 14 Plagioclase 49 — Plagioclase 40 Biotite 12 — Biotite 6
		Further along both branches to eastern end of dyke, T.S. 8267-8271: Phenocrysts: Quartz, Orthoclase, Oligoclase. Accessories: As above	Groundmass: Quartz, Orthoclase, Oligoclase, Biotite (less). Secondaries: As above.	100 — 100 Others 0.6 — Others 0.2
PART 2 Porphyritic microgranodiorite of O'Connor's Hill (T.S. 8274-8276 incl.).	Phenocrysts up to 4 mm across in fine-grained groundmass.	Phenocrysts: Quartz, Andesine, Biotite, Hornblende Groundmass: Quartz, Orthoclase, Oligoclase, Biotite.	Accessories: Zircon, Apatite, Hematite, Ilmenite. Secondaries: Chlorite and sphene, Sericite, Limonite	Groundmass is aplitic in appearance and texture,
PART 3 Porphyritic granodiorite of Stony Creek (T.S. 8322).	Phenocrysts up to 16 mm across in fine-grained groundmass with a 'salt-and-pepper' appearance	Phenocrysts: Oligoclase (with zoning and exsolution): Biotite (rare); Hornblende (rare). Groundmass: Quartz, Orthoclase, Plagioclase (zoned from andesine (core) to oligoclase), Biotite, Hornblende.	Accessories: Zircon, Apatite, Ore minerals. Secondaries: Chlorite and sphene, Sericite.	
PART 4 Coarse-grained granodiorite plug (T.S. 8323-8325 incl.).	Coarse-grained, with a small amount of micrographic groundmass.	Essentials: Quartz, Orthoclase (perthitic in some grains), Andesine, Biotite. Accessories: Hornblende (up to 6mm long), Zircon, Apatite, Allanite, Ore minerals, Sphene Secondaries: Limonite, Chlorite and sphene, sericite (rare).		

the north-east. Petrography of the rock is given in Table 4, Pt 2.

The contact of this body with G3 is nowhere exposed, but at four places around the contact zone, boulders of granodiorite finer in grain than the typical G3 were found. A thin section (TS 8277) of this rock shows it to be recrystallized granodiorite (G3). The section contains aggregates of many small biotite grains, commonly grouped around hornblende crystals. Larger biotite crystals are frayed at the edges, and small grains of magnetite have formed in the biotite. Some large hornblende and biotite crystals show replacement by the quartz and felspars. Metamorphism of the granodiorite G3 by the microgranodiorite is indicated.

The main microgranodiorite intrusion contains at least four rafts of G3 granodiorite, the largest 220 yds long. These stand out in the landscape as sizeable corestones, in contrast to the much smaller boulders of microgranodiorite. Also present in this body are four substantial masses of aplite which form the tops of adjacent hills, suggesting that they are the remains of one flat sheet. The aplites are quite normal—Table 6, Pt 3.

The porphyritic microgranodiorite of O'Connor's Hill is clearly later than G3, as it has caused recrystallization of the granodiorite, and contains rafts of it. It is older than the granodiorite of Stony Ck, as plugs of this rock have been injected along the contact zone of G3 and the microgranodiorite.

(9) PORPHYRITIC GRANODIORITE OF STONY CREEK

This intrusion occupies an area of 1·8 square miles, and lies 1 mile N. of the Cobaw Ranges, immediately S. of the porphyritic microgranodiorite of O'Connor's Hill (Fig. 2). The long axis of the body is parallel to that of the Cobaw Granite massif. A small off-shoot is situated 2 miles to the north-east, slightly finer-grained than the main Stony Ck body. The rock has a distinctive porphyritic appearance, with ovoid phenocrysts of felspar up to 15 mm long, set in a fine-grained 'salt and pepper' groundmass (Table 4, Pt 3). Except for its texture, the rock is similar to the typical granodiorite of G3, and the contact between the two rocks is sharp.

(10) COARSE-GRAINED GRANODIORITE PLUG

This plug, which measures 250 yds across, crops out 1 mile SW. of Baynton, and is associated with the two off-shoots from the intrusions at O'Connor's Hill and Stony Ck (Fig. 2). It is very like the granite G2 in appearance, except that it contains prisms of hornblende up to 12 mm long. The petrography of the rock is summarized in Table 4, Pt 4. No contact with host rocks is exposed.

(11) EIGHT SMALL INTRUSIONS ASSOCIATED WITH G4

These intrusions occur in three groups around the margin of G4, and are numbered from 1 to 8 in Fig. 2. Petrographic descriptions appear in Table 5.

TABLE 5

Eight small intrusions around margin of G4

ROCK	TEXTURE	MINERAL	CONTENT	REMARKS
1. Porphyritic micro-adamellite (T.S, 8319, 8320)	Phenocryste up to 4 mm long in fine-grained, allotriomorphic groundmass.	Phenocrysts: Quartz, Orthoclase, Biotite Groundmass: Quartz, Orthoclase, Oligocisse.	Accessories: Hornblende, Zircon, Apatite. Secondaries: Chlorite, Sericite.	Modal Composition: (average of T.S. 8319 and 8320). Parts of the dyks bavs more plagio-clase than orthoclase. Quartz 31 Orthoclase 37 Plagioclase 27 Biotite 5 100 Hornblende 0.
2. Fins-grained granite (T.S. 8317)	Has a few phenocrysts up to 5 mm long.	Phenocryats: Oligoclase, intergrown with a small amount of orthoclase. Groundmass: Quartz, Orthoclase, Oligoclase, Biotite.	Accessories: Hornblende, Zircon, Apatite, Allanite, Sphene, Magnetite. Secondaries: Chlorite, Sericite.	
3. Porphyritic horn-blende granodiorite (T.S. 8318).	Medium-grained.	Phenocrysts: Andesine. Groundmass: Quartz, Orthoclase, Oligoclase, Biotite, Hornblende.	Accessories: Zircon, Apatite, Ore minerals. Secondaries: Chlorite, Sericite.	Hornblende is abundant
4. Porphyritic micro-adamellite (T.S. 8313, 8314).	Phenocryste up to 3 mm long in fine-grained groundmass.	Phenocryats: Quartz, Orthoclase, Andesine, Biotite, Hornblende. Groundmasa: Quartz, Orthoclase, Andesine, Biotite, Hornblends	Accessories: Zircon, Apatite, Ore minerals. Secondaries: Chlorite, Sericite.	Andesine phenocryste are str zoned. Modal Composition (average of T.S. 8313 and 8314): Quartz 35 Orthoclase 29 Plagioclase 26 Biotite 9 Hornblende 1 100 Others 0.
5. Hornblende grano-diorite (T.S. 8316).	Fine-grained.	Phenocrysts (rare); Oligoclase. Groundmasa: Quartz, Orthoclase, Oligoclase, Biotite, Hornblende.	Accessories: Zircon, Apatite, Ore minerals. Secondaries: Chlorite, Sericite.	Hornblende is abundant. Rock has dark, speckled appearance.
8. Porphyritic micro-granodiorite (T.S. 8315)	Phenocryats up to 15 mm long in fine-grained groundmass.	Phenocryats: Quartz, Andesine, Biotite Groundmasa: Quartz, Andesine, Biotite.	Accessories: Hornblende, Sphene, Zircon.	Biotite phenocrysts are aggregates small individual crystals.
7. Porphyritic microgranodiorite, not thin sectioned.				
8. Uralite dolerite (T.S. 8312).	Medium-grained, ophitic.	Essentials: Sodic labradorite (An_{52}); Hornblende; Titanaugite; Ilmenite (skeletal); Apatite. Secondaries: Chrysotile (aggregates); Tremolite and Actinolite; Sericite.		Labradorite forms albite-twinned lath Titanaugite is bright pink and stro pleochroic. Chrysotile may be aft olivine. Tremolite and actinolite ar after augite

The three largest intrusions (No. 1, 2, and 3) form one group near the eastern end of G4, on the road from Lancefield to Baynton (Fig. 2). They consist of a large elongate body of porphyritic microadamellite (1), a smaller mass of fine-grained granite (2), and another of porphyritic hornblende granodiorite (3). The second group (No. 4, 5, and 6) is situated at the western end of G4, N. of the road from Cobaw to Piper's Ck, and comprises a dyke of porphyritic microadamellite (4), a plug of fine-grained hornblende granodiorite (5), and a smaller plug of porphyritic microgranodiorite (6). Lastly, two very small outcrops (No. 7 and 8) are present 2½ miles NNE. of the second group, E. of the road from Piper's Ck to Baynton. The first is a plug of porphyritic microgranodiorite (7), the second an exposure of uralitized dolerite (8), which contains sodic labradorite and a very bright pink variety of titanaugite. The occurrence and origin of this dolerite remain unexplained.

(12) PORPHYRITIC MICROGRANODIORITE AND PORPHYRITIC MICRODIORITE DYKES

In contrast to the porphyritic microgranites (4) which intrude the country rocks, the porphyritic microgranodiorites and microdiorites crop out entirely within the Cobaw Granite, though strikes are again generally N.-S. Most of the dykes are microdiorites; petrographic descriptions are summarized in Table 6, Pt 1 & 2. The dykes have been found only in the western half of the massif, but this is not a result of the mapping, as it was the eastern half that was covered in more detail, during the study of the xenoliths.

TABLE 6

Final minor intrusions

ROCK	TEXTURE	MINERAL CONTENT		REMARKS
ART 1 orphyritic microgranodiorite dykes (T.S. 8376-8378 incl.).	Phenocrysts up to 5 mm across in fine-grained groundmass.	Phenocrysts: Quartz (corroded by groundmass); Andesine (euhedral). Groundmass: Quartz, Orthoclase, Sodic plagioclase Biotite.	Accessories: Zircon, Sphene, Hornblende, Allanite, Ore minerals Secondaries: Epidote, Chlorite, Sericite.	Biotite is almost completely replaced by chlorite. Groundmass is patchy, some areas have minute micrographic intergrowths, other parts are granular.
ART 2 orphyritic microdiorite dykes (T.S. 8379-8382 incl.).	Phenocrysts up to 7 mm across in fine-grained groundmass.	Phenocrysts: Orthoclase (not common); Oligoclase or Andesine (commonly euhedral); Biotite (not common). Groundmass: Quartz, Orthoclase, Oligoclase, Biotite.	Accessories: Zircon, Apatite. Secondaries: Muscovite, Chlorite, Calcite.	Groundmass is generally patchy; small-scale spherulitic or micrographic intergrowths form patches in the more granular material. Plagioclase phenocrysts are replaced by aggregates of calcite and muscovite, and calcite and chlorite, in T.S. 8382.
ART 3 plite (T.S. 8351-8361 incl.).	Variable; areas of minutely delicate micrographic intergrowth are interspersed with areas of coarser granular texture in the same thin section.	Essentials: Quartz, Orthoclase. Secondaries: Chlorite (after biotite), Kaolin (after orthoclase).	Accessories: Oligoclase, Biotite, Zircon, Ore minerals, Muscovite, Hematite, Apatite, Allanite.	A bright orange, isotropic mineral in T.S. 8357 may be a chlorite. Muscovite forms rosettes up to 12 mm across in T.S. 8358.
ART 4 Pegmatite (T.S. 8362-8365 incl.).	Coarse-grained quartz is commonly moulded on orthoclase.	Essentials: Quartz, Orthoclase, Oligoclase.	Accessories: Muscovite, Biotite, Tourmaline.	In T.S. 8364, oligoclase exceeds orthoclase in amount.

(13) (a) APLITE

Aplite is common throughout the Cobaw Granite, both as flat sheets, and as thin dykes and veins generally an inch or less wide and many feet in length. The latter are generally straight, but a few veins are sinuous. Most of the aplite is found within the granitic rocks, but in McIvor Ck and Mollison's Ck, veins of aplite and pegmatite a few feet long occur at the contact of the granite G2 with the sediments. Aplite and pegmatite also form composite veins.

Aplite is commonly present at the contact of G2 and G3 (see above), and large circular bodies of aplite are also found. Four of these lie inside the microgranodiorite of O'Connor's Hill, and include the three largest, each 300 yds in diameter and probably parts of the one sheet. Two more are present within a mile of this intrusion (Fig. 2). Descriptions of the aplites are given in Table 6, Pt 3. The larger bodies show no difference in thin section from the small veins.

(b) PEGMATITE (Table 6, Pt 4)

This is not a common rock, and usually forms dykes about 6″ wide, with a central zone of aplite up to 2″ wide. At Pyalong, a tongue of granite (G2) has been injected along the strike of the Silurian country rock, and towards the margins, and in veins invading the sediments, the granite is pegmatitic; normal pegmatite is present at the contacts.

The paucity of pegmatite and abundance of aplite in the Cobaw Granite indicates that the water contents of the magmas were low, even at the end of crystallization of the main bodies of granite and granodiorite. This is in harmony with the low content of other volatiles, indicated by the scarcity of such minerals as tourmaline, topaz, and fluorite.

(c) REEF QUARTZ

Veins of quartz are also rare in the granitic rocks. They are more abundant in the country rocks, and 2 miles W. of Sidonia an abandoned shaft and drive follow a former E.-W. quartz reef in the Ordovician hornfels. Isolated rounded pieces of reef quartz up to 2″ across were found in G2 and G3. These fragments are most likely xenoliths of reef quartz originally present as veins in the sediments.

Xenoliths

XENOLITHS IN THE GRANITE G2

Xenoliths in the granite are few relative to those in the granodiorite G3. In some places they are fairly plentiful and, where this is so, the xenoliths are commonly in swarms of about a dozen in an area 5 to 10 ft square. Solitary xenoliths may be up to 3 or 4 ft across, so possibly the swarms of small individuals represent large blocks later broken up. The xenoliths lie parallel to the planar structure that is characteristic of the granite (Pl. 35, fig. 1).

DESCRIPTIONS:

XENOLITHS OF SEDIMENTARY ORIGIN (Table 7, Pt 1)

Most of these are fine-grained and tabular, their shape arising from the prominent bedding and close jointing in the country rocks. They are usually straight-sided, the corners are only slightly rounded, and embayments are rare. Thin veins of granitic material commonly lie parallel to the bedding of the xenoliths. Some xenoliths are lenticular (Pl. 35, fig. 1), and a few are roughly equant; in the latter case a faint lineation, which probably represents the original bedding, can generally be made out on a freshly broken surface, and there may also be granitic veins injected parallel to the bedding. Very few xenoliths show strewing at the contact; edges are almost everywhere sharp and clean (though see Singleton 1949, p. 100). The xenoliths are almost invariably dark grey, and only rarely contain felspar porphyroblasts. The minerals present are the same as the principal minerals in the granite, and so it appears that equilibrium between the host granite and the inclusions has been reached. TS 8419, from a locality 3 miles SSE. of Tooborac, is different from the fine-grained examples, in that the rock is coarser-grained and composed chiefly of metamorphic minerals, particularly large xenoblastic cordierite crystals. These were probably formed by amalgamation of smaller crystals present in the original hornfels, as found in McIvor Ck, 3 miles to the NW. (cf. Tattam 1925, p. 242).

TABLE 7

Xenoliths in granite (G2) and granodiorite (G3)

ROCK	TEXTURE	MINERAL CONTENT	REMARKS
Xenoliths in granite, G2. PART 1 Sedimentary xenoliths (T.S. 8418, 8420, 8421).	Fine-grained, granoblastic: quartz, and feldspar form poikiloblasts enclosing the small grains of biotite and feldspar. Rare porphyroblasts are present.	Porphyroblasts: Oligoclase (T.S. 8421 only); Biotite (T.S. 8421 only). Groundmass: Quartz, Orthoclase, Oligoclase or Andesine, Biotite (abundant). Accessories: Zircon, Apatite. Secondaries: Chlorite (after biotite), Sericite (after plagioclase).	T.S. 8418 has no orthoclase, is slightly coarser-grained, and subidioblastic.
T.S. 8419.	Medium-grained, xenoblastic.	Composed of cordierite (enclosing needles of sillimanite), and smaller amounts of quartz, andesine, biotite, and muscovite. Accessories: Apatite, Zircon, Ore minerals, Spinel. Secondary: Chlorite.	A recrystallized cordierite hornfels.
PART 2 Cognate xenoliths (T.S. 8422, 8423).	Medium-grained subidioblastic.	Essentials: Quartz, Andesine, Biotite. Accessories: Zircon, Apatite. - - - - - Quartz, Orthoclase, Oligoclase, Biotite. Zircon, Apatite.	T.S. 8422. - - - - - T.S. 8423.
Xenoliths in granodiorite, G3. PART 3 Sedimentary xenoliths (T.S. 8393-8395 incl.)	Rare porphyroblasts in a fine-grained, granoblastic groundmass.	Porphyroblasts: Oligoclase (T.S. 8393). Groundmass: Quartz, Orthoclase, Oligoclase or Andesine, Biotite. Accessories: Zircon, Apatite, Allanite. Secondary: Chlorite.	Biotite is very abundant. Orthoclase is subordinate to plagioclase.
T.S. 8396 (and 8397).	Heterogeneous,	The thin section has fine-grained hornfelsic areas of quartz, orthoclase, andesine, biotite, ore minerals, sphene, and apatite. Other parts have large sillimanite crystals containing small grains of green spinel, and myriads of tiny zoisite crystals, which are arranged in patterns similar to herring-bone structure. There are patches of coarse-grained cordierite containing sillimanite needles, granoblastic areas of zoisite and sillimanite, and clots composed solely of many small crystals of biotite.	A recrystallized cordierite hornfels.
Igneous xenoliths. PART 4; Group (i) Fine-grained porphyroblastic xenoliths (T.S. 8398-8409 incl.).	Porphyroblasts up to 6mm across in subidioblastic groundmass.	Porphyroblasts: Quartz, Oligoclase or Andesine, Biotite, Hornblende. Groundmass: Quartz, Plagioclase (zoned from andesine (core) to oligoclase), Biotite, Hornblende (abundant). Accessories: Sphene, Diopside, Zircon, Apatite, Hematite, Ilmenite, Allanite, Augite, Epidote. Secondaries: Chlorite, Sericite.	Most porphyroblasts are of plagioclase. Quartz in groundmass forms poikiloblasts. Hornblende porphyroblasts show replacement by quartz of groundmass. Diopside is usually enclosed by hornblende.
PART 5; Group (ii) Fine-grained non-porphyroblastic xenoliths (T.S. 8410-8412 incl.).	A slight patchiness is present in the distribution of light and dark minerals.	Essentials: Quartz, Andesine, Biotite, Hornblende, Diopside (T.S. 8411 only). Accessories: Apatite, Hematite, Zircon. Secondaries: Sericite, Chlorite, Calcite.	Diopside is abundant in T.S. 8411. Hornblende shows replacement by quartz and feldspar.
PART 6; Group (iii) Medium-grained xenoliths (T.S. 8413-8415 incl.).	'Dioritic' in appearance.	Essentials: Quartz, Plagioclase (zoned from andesine (core) to oligoclase), Biotite, Hornblende (more abundant than biotite), Diopside (T.S. 8414 only). Accessories: Sphene, Apatite, Allanite, Zircon, Ore minerals. Secondaries: Sericite, Chlorite, Calcite.	Hornblende shows replacement by quartz and feldspar.

XENOLITHS OF COGNATE ORIGIN (AUTOLITHS) (Table 7, Pt 2)

These are far less abundant than those of sedimentary origin, and only two were sampled. They are spheroidal or ovoid and appear as biotite-rich areas in the granite. In thin section the texture is very close to ordinary granitic texture, and they consist entirely of granitic minerals.

DISCUSSION:

Most of the xenoliths in the granite are tabular or lenticular, and are derived from the Lower Palaeozoic sediments. Very few were of the coarse-grained, heterogeneous type such as TS 8419, which is rich in cordierite. Almost all the xenoliths are fine-grained, and consist of granitic minerals. The low proportion of cordierite-bearing xenoliths is a reflection of the subordinate amount of cordierite-bearing hornfels in the aureole, which consists mostly of sericite hornfels. Hence, nearly all the blocks that were stoped off the walls during the rise of the granite would have consisted of quartz, sericite, and biotite (see above). The xenoliths consist of quartz, orthoclase, oligoclase, and biotite, an assemblage indicating the hornblende-hornfels facies of contact metamorphism (Turner & Verhoogen 1960, p. 514). The mineralogy suggests that the sericite has been converted to felspar, supporting the principles of Bowen (1922).

As the xenoliths are composed of the minerals of granite, 'A certain amount of mechanical disintegration might cause the strewing about of these products in such a way as to make them an integral part of the mass, but there should be no solution.' (Bowen 1922, p. 561). This may account for the rounding of the corners and rare embayments seen in the xenoliths. The lack of debris around the xenoliths shows that any strewing occurred when the granite was moving, so that the debris was cleared away.

The autoliths are presumably fragments of early crystallized granite, brought up by the later movement of the magma.

XENOLITHS IN THE GRANODIORITE G3

Xenoliths in G3 are generally in large numbers (Pl. 35, fig. 2), but in places the granodiorite contains only a few of them. The xenoliths are usually spheroidal or ovoid, and few exceed a foot in length. Owing to their fine grain, the xenoliths weather more slowly than the granodiorite, and so project from the surfaces of the boulders. In three localities the long axes of the xenoliths are parallel, but generally they show no such alignment.

DESCRIPTIONS:

XENOLITHS OF SEDIMENTARY ORIGIN (Table 7, Pt 3)

In the hand-specimen these appear exactly like their counterparts in the granite, being dark and uniformly fine-grained, usually tabular or lenticular, and commonly veined with granitic material. A few coarse-grained recrystallized varieties also occur.

In thin section, the fine-grained xenoliths have a granoblastic texture, and small porphyroblasts of oligoclase are present in TS 8393. TS 8394 is of a very small xenolith, and shows lenticular patches of different grain-size and mineral content, probably indicating differences between individual laminae in the original sediment. TS 8396 and 8397 are cut from one of the unusual xenoliths of coarsely recrystallized hornfels, which shows patches of different textures and mineralogy; Table 7, Pt 3.

XENOLITHS OF IGNEOUS ORIGIN

These are far more abundant than those of sedimentary origin. The hand-specimens show a number of differences, and they can be divided into three main groups:

Group (i)	Fine-grained porphyroblastic xenoliths: TS 8398-8409 incl. (Table 7, Pt 4).
Group (ii)	Fine-grained non-porphyroblastic xenoliths: TS 8410-8412 incl. (Table 7, Pt 5).
Group (iii)	Medium-grained xenoliths: TS 8413-8415 incl. (Table 7, Pt 6).

The three groups are distinct from each other, both in hand-specimen and under the microscope.

GROUP (i): FINE-GRAINED PORPHYROBLASTIC XENOLITHS (Table 7, Pt 4)

These are sharply defined, pale to medium grey, ovoid patches in the granodiorite (Pl. 35, fig. 2), studded with white or cream felspar porphyroblasts up to 12 mm across. Hornblende porphyroblasts are also present, though less commonly, and are up to 6 mm long. Petrographically, this group can be divided into two subgroups. In subgroup (a), the biotite is pleochroic from reddish brown to very pale brown, and is more abundant than hornblende; also, the poikiloblastic nature of the quartz is prominent. In subgroup (b), the texture is rather finer-grained and not so poikiloblastic, and the biotite is pleochroic from greenish brown to pale yellow and is generally less abundant than the hornblende. In addition, there is less quartz, and the plagioclase is lath-shaped, so that the rock has a faintly 'doleritic' texture.

GROUP (ii): FINE-GRAINED NON-PORPHYROBLASTIC XENOLITHS (Table 7, Pt 5)

These are dark, uniformly fine-grained rocks, with a slight patchiness of colour but no porphyroblasts.

GROUP (iii): MEDIUM-GRAINED XENOLITHS (Table 7, Pt 6)

These are coarser-grained than the xenoliths of the first two groups, and hornblende is prominent in hand-specimen. They have a speckled 'dioritic' appearance, and strewing at the margins with the enclosing granodiorite is common.

DISCUSSION:

The first type—i.e. lenticular or tabular, non-hornblende-bearing xenoliths, are clearly derived from the Lower Palaeozoic sediments. However, the hornblende-bearing xenoliths are not so easily assigned an origin, for although they are most probably of igneous origin, there are at least three sources capable of producing the same mineralogy of these xenoliths. They are:

(a) Basic segregations (autoliths) formed early in the granodiorite;
(b) A chilled border phase of the granodiorite;
(c) Cambrian basic volcanics from the country rocks.

The first source, basic segregations, may be represented by some of the coarser-grained type of hornblende-bearing xenolith—i.e. those of group (iii). These generally have strewed borders, and are 'dioritic' in aspect, suggesting their origin from a more mafic phase (Bowen 1922, p. 539; Turner & Verhoogen 1960, p. 157). Pieces of a chilled border phase, formed early in the solidification of the granodiorite and later disrupted, could be some of the fine-grained xenoliths, with or without porphyroblasts—i.e. those of subgroup (i) a, and group (ii).

Xenoliths of the third possible origin, the Cambrian basic extrusive rocks, may be the quartz-poor, faintly 'doleritic' xenoliths of subgroup (i) b. Thomas & Smith (1932) described an occurrence of granite intruding norite, the two rocks reacting to form hybrid bodies of mica diorite. Xenoliths of these mica diorite hybrids in the granite are very similar to the ovoid igneous xenoliths discussed here, more especially those without porphyroblasts. They concluded that many so-called autoliths (basic segregations) may be true xenoliths derived from unexposed basic rocks. Some of the 'dioritic' xenoliths (group iii) could also come from intruded basic rocks (Turner & Verhoogen 1960).

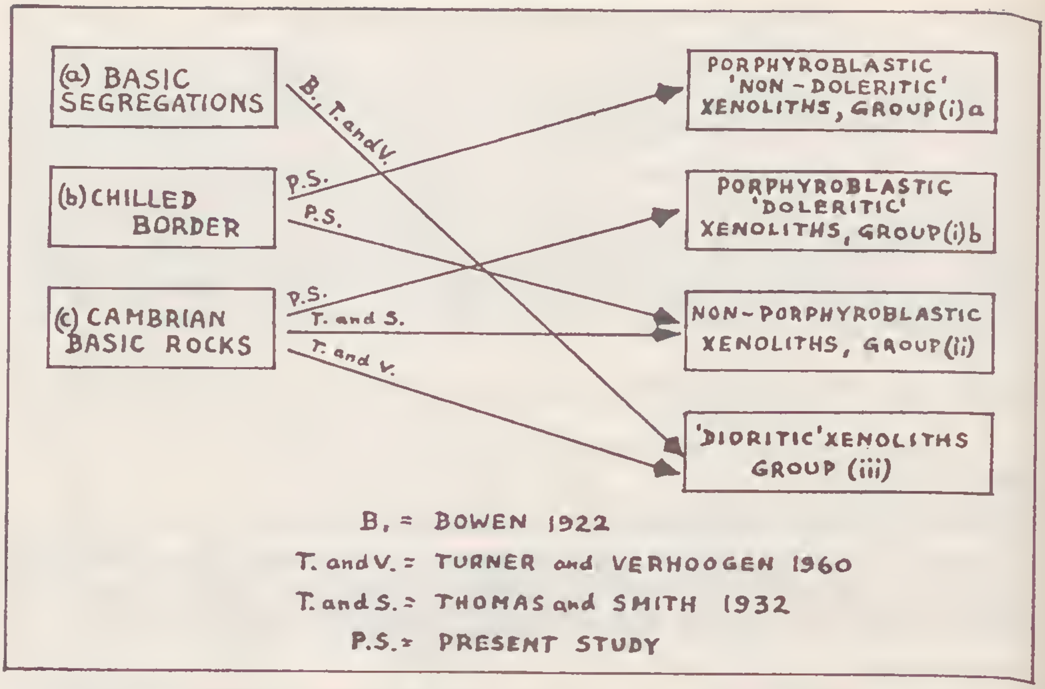

(a) BASIC SEGREGATIONS
(b) CHILLED BORDER
(c) CAMBRIAN BASIC ROCKS
B. T. and V.
P.S.
P.S.
P.S.
T. and S.
T. and V.
PORPHYROBLASTIC 'NON-DOLERITIC' XENOLITHS, GROUP(i)a
PORPHYROBLASTIC 'DOLERITIC' XENOLITHS, GROUP(i)b
NON-PORPHYROBLASTIC XENOLITHS, GROUP(ii)
'DIORITIC' XENOLITHS GROUP (iii)
B. = BOWEN 1922
T. and V. = TURNER and VERHOOGEN 1960
T. and S. = THOMAS and SMITH 1932
P.S. = PRESENT STUDY

FIG. 4—Schematic diagram showing possible xenolith sources available to the granodiorite G3, and the resulting xenoliths.

To sum up, Fig. 4 illustrates schematically the possible original rocks and the xenoliths they could give rise to, incorporating the views of the above authors and those from the present study. In view of the various sources available for each type of xenolith, it is possible that not all the sources have in fact been used. However, it is difficult to check this, except for those xenoliths derived from the Cambrian basic rocks. Xenoliths of the other two possible origins (a and b above and in Fig. 4) could be derived from anywhere in or around the granodiorite body, as there is no reason for postulating the formation of basic segregations or an early chilled phase in one restricted part of the granodiorite. However, the Cambrian rocks do form a restricted source, as they crop out along a single narrow belt in the country rocks which surround the granite massif. It seems very probable that this belt existed in the country rocks forming the roof above the granitic rocks, and so it was thought that any xenoliths derived from the Cambrian rocks would probably be concentrated in a zone following the projected strike of the Cambrian belt, assuming that there had been no convection currents in the magma. Away from the outcrop of the Cambrian rocks, hornblende-bearing xenoliths should have only been derived from the other two possible sources (a and b above), and so here their numbers should be fewer in proportion to the non-hornblende-bearing xenoliths, and in the zone following the strike of the Cambrian belt, their numbers should be greater.

To test this, three traverses were run across the projected line of strike of the Cambrian belt, and a fourth control traverse was run at the other end of the granodiorite (G3), well away from any known Cambrian rocks (Fig. 2). On each traverse, at stations roughly 1,000 yds apart, fifty xenoliths were counted (or as many as possible up to this number), and after examination of the hand-specimens, assigned sedimentary or igneous origins. The ratio:

$$\frac{\sum \text{ igneous (hornblende-bearing) xenoliths}}{\sum \text{ sedimentary (non-hornblende-bearing) xenoliths}}$$

shows a marked increase over the line of strike of the Cambrian belt, along all three traverses, and no rise along the control traverse (Fig. 5). Thus there is a concentration of hornblende-bearing xenoliths in this zone, and this shows that at least some of the xenoliths were derived from the Cambrian basic rocks. As a point of interest, it is noticeable that the increase in the ratio along the northern traverse takes place over a shorter distance than along the middle and southern traverses, and it seems reasonable to suppose that this resulted from the narrowness of the Cambrian belt north of the massif, relative to its width in the south. This concentration of hornblende-bearing xenoliths shows that a certain amount of small-scale piecemeal stoping of the roof over the granodiorite took place.

The overall mineralogical similarity of the xenoliths is readily explained, and supports Bowen's Reaction Principle. Changes in the sedimentary xenoliths would have followed similar lines to those that took place in the sedimentary xenoliths in the granite (i.e. conversion of sericite to felspar). Basic segregations in the granodiorite would have consisted initially of augite and calcic andesine or labradorite, but once hornblende started to crystallize in the magma, the augite would have reacted to give additional hornblende and eventually some biotite, and the plagioclase would have become more sodic. The chilled border phase possibly contained some augite and calcic andesine (as well as a substantial amount of hornblende), and these too would have been made over to phases later in the reaction series. The stoped blocks of Cambrian basic rocks were already metamorphosed to epidiorite before and during engulfment in the granodiorite magma, and so would have undergone mainly recrystallization and formation of some biotite.

The absence of orthoclase in the igneous xenoliths is interesting, and this suggests that only enough potassium was introduced from the magma to form the biotite in the xenoliths. The large crystals of andesine and oligoclase in the xenoliths of group (i) are euhedral, and show no signs of corrosion. Hence, they are probably porphyroblasts, not blastophenocrysts, and so metasomatic introduction of felsic material (sodium and silicon) from the magma is indicated. The introduction of some constituents, and removal of others (mainly iron and magnesium) is also supported by the texture of all the igneous xenoliths, particularly the 'dioritic' xenoliths of group (iii). These show that the hornblende has been substantially replaced by quartz and plagioclase, and presumably the initial inequilibrium resulted from the difference in composition between the magma and the basic rocks. The absence of any crowding of the small grains of biotite and hornblende around the felspar porphyroblasts also indicates that these grains were metasomatically replaced, and not merely pushed aside by the growing porphyroblasts.

Structure

COUNTRY ROCKS

The Lower Palaeozoic rocks of the Central Victorian region were deformed during the Middle Devonian Tabberabberan Orogeny. The Cambrian rocks were complexly folded and faulted, and the detailed structure has proved difficult to determine (Thomas & Singleton 1957). The Ordovician rocks were compressed into similar folds of small width and great vertical extent, plunging N. or S.; the

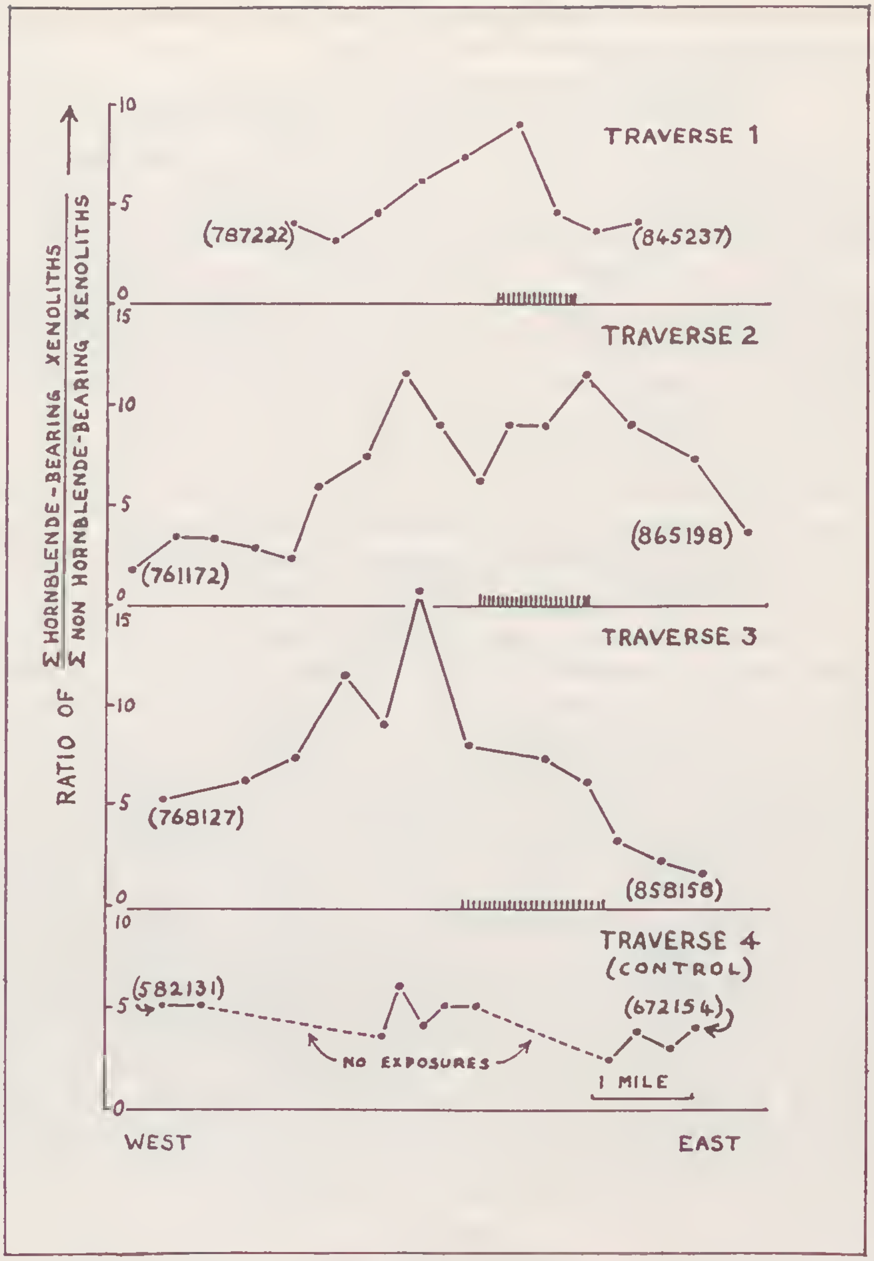


FIG. 5—Results of xenolith traverses, shown in graphical form. For each traverse, distance travelled E.-W. (at 2 miles to 1") forms the abscissa, and the ratio of the number of igneous xenoliths to the number of sedimentary xenoliths, at each station, has been plotted along the ordinate. Vertical hatching represents position and width of Cambrian belt of basic rocks. Full explanation in text.

folds are generally aligned a few degrees W. of N. Graptolites are preserved, and these have enabled the detailed structure of the Lower Ordovician to be worked out (Thomas 1939). This has revealed brachyanticlinoria and brachysynclinoria to be the major structures developed, and their axes show the same N.-S. trend as the individual folds (Fig. 6). The Silurian rocks were thrown into long, arcuate

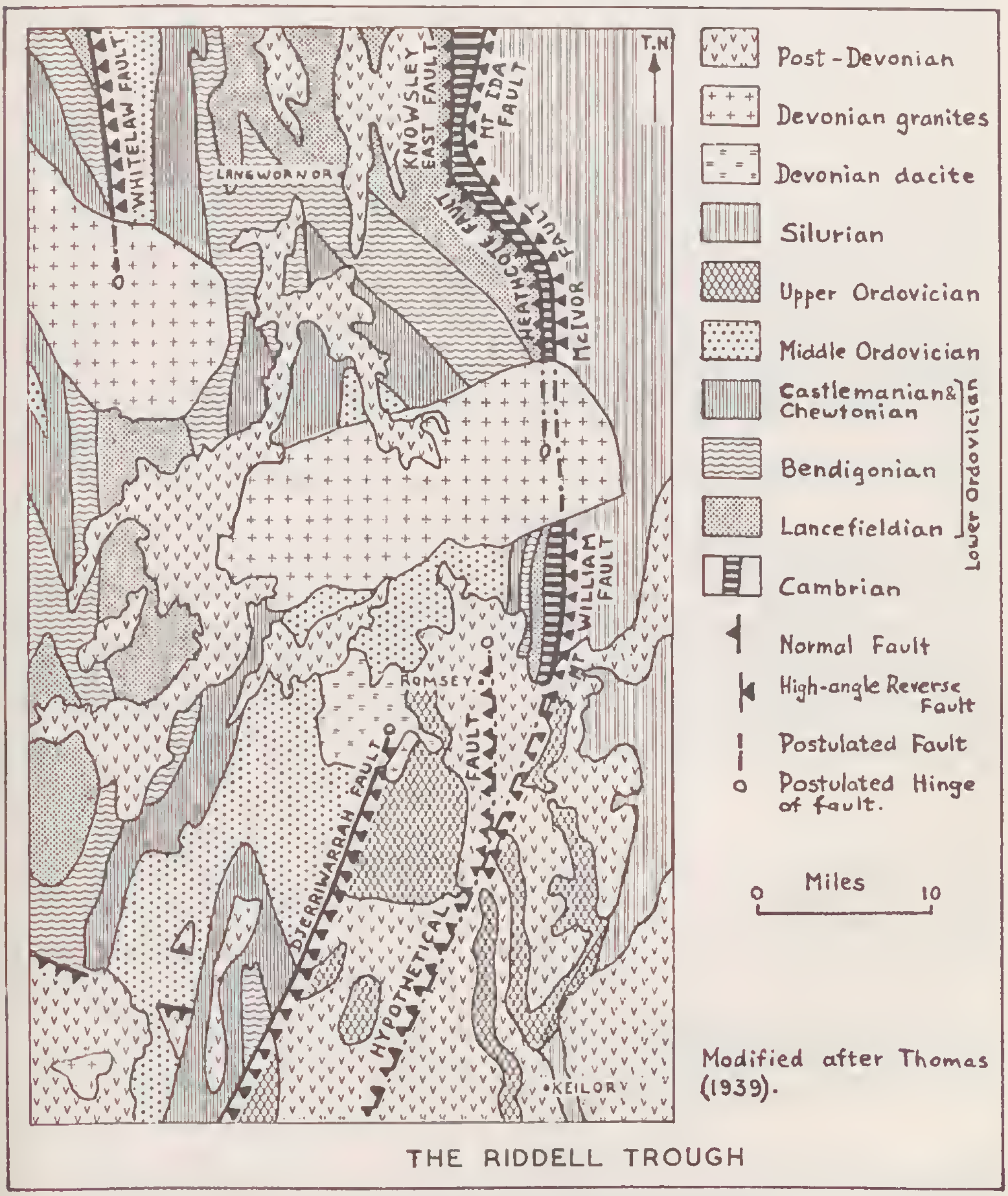


FIG. 6—Geological map of the Riddell Trough.

folds that are more open than those in the Ordovician, and with little or no plunge (Thomas 1939, Williams 1964).

Soon after the folding there occurred large-scale high-angle faulting, mostly reverse, with throws of many thousands of feet (Thomas 1939, Thomas & Singleton 1957). The western faults of the Mt William-Heathcote-Colbinabbin Belt—i.e. the Heathcote Fault and the Knowsley East Fault, are of much smaller throw and apparently are normal faults, as they bring the Cambrian against younger rocks—viz. Lancefieldian, the lowest zone in the Lower Ordovician.

THE RIDDELL TROUGH

In the region of the Cobaw Granite, the Ordovician rocks form the Riddell Synclinorium or Riddell Trough (Thomas 1939), extending from Langwornor in the north at least 55 miles to Keilor in the south, with a maximum width of 22 miles (Fig. 6). The trough is bounded on the west by brachyanticlinoria, and on the east by the Mt William-Heathcote Belt. The northern end is a S.-plunging synclinorium, but the southern end is complicated by faulting. These faults are the Djerriwarrah Fault, and a hypothetical fault which was postulated by Thomas (1939) to explain the cutting out of the Cambrian and Lower Ordovician rocks S. of Romsey, near Lancefield. This area is covered by Tertiary basalt, and the existence of the fault remains unproved. I regard it as a hinged normal fault, west block down, its hinge situated in the north, a little S. of Lancefield. The Djerriwarrah Fault is a reverse fault, east block down, and also hinged in the north, so that the block bounded by this fault and the hypothetical fault is a graben hinged in the north, preserving Upper Ordovician rocks at the surface.

INTRUSIVE ROCKS

(i) GENERAL STRUCTURE

The Cobaw Granite possesses a ring structure, with a large ring of coarse-grained granite (G2) surrounding a core of granodiorite (G3) (Fig. 2). The whole massif has the outline of a modified rectangle. The N.-S. boundaries are subcircular in plan, whereas the E.-W. boundaries are very nearly straight and parallel. This subrectangular shape is shown by both the outer contact of G2 and the inner

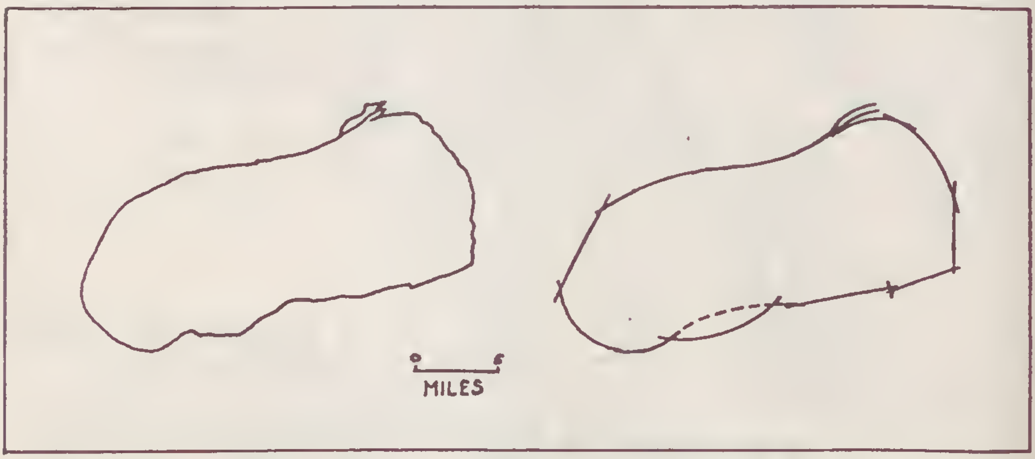


FIG. 7—Diagram showing outline of the Cobaw Granite (left) and the arcuate trends of segments of this outline (right).

contact of G2 and G3. The inner contact is particularly regular, for the E.-W. contacts trend exactly parallel to each other, and the N.-S. boundaries closely approximate semicircles.

In detail, the E.-W. contacts of G2 with the country rock are composed of segments that have arcuate trends (Fig. 7). One of the arcs on the northern boundary is of opposite curvature from the others, so that the boundary is slightly re-entrant; perhaps another re-entrant arc existed where G4 was emplaced, so giving the whole outer granite contact a 'centre of symmetry', except for the wide corner in the south-east. This corner, and also those in the north-east and south-west are discussed below. The contacts themselves are smooth over distances of a few hundred yards, but show embayments when considered as a whole.

(ii) Attitudes of Contacts

Clear vertical sections across the contacts are non-existent. At Hayes's Hill, 4 miles SW. of Tooborac, 400 vertical ft of the outer contact can be seen when the eastern side of the hill is viewed from a distance. At other places, consideration of the strike of the contact and its intersection with the contour lines of the military maps (1" to 1 mile) shows that the contact is usually close to vertical (Fig. 8). At Pyalong, and immediately W. of Ben Loch, the outer contact dips steeply inwards, and N. of Sidonia it may dip steeply outward; however, in general the outer contact is vertical. The inner contact is nowhere exposed in vertical section, but the intersection of the strike with the contours indicates that it too is close to vertical (Fig. 8).

(iii) Screens of Older Rocks

Around the contact of G2 and G3, no screens of sedimentary wall rock have been found anywhere between the two igneous rocks. However, there is an elongate raft of country rock in the SE. corner of the granite ring (Fig. 2), 100 yds from the outer contact, and in the Tooborac area there are screens of sedimentary country rock between the hypersthene porphyrite (G1) and the medium-grained granite dyke, and between the granite dyke and the outer contact of G2. The larger screens are still attached to the country rock, but the smaller ones are completely surrounded by igneous rocks at this level. The remains of a possible acid dyke that intruded the country rock before the emplacement of G3 are preserved near the southern boundary of the granodiorite of Stony Ck. However, screens along the actual contact of G2 and G3 are absent.

(iv) Wide Corners

Three of the four corners of the ring of granite are far wider than the rest of the ring. The SW. and NE. corners have arcuate outer boundaries, and in the NE. corner (at Tooborac) the dykes of hypersthene porphyrite (G1) and medium-grained granite also have arcuate trends. Hence the existence of arcuate fractures outside the general line of fracturing is indicated. There is no exposure in the SW. corner.

The SE. corner is bounded by two straight contacts which meet at an angle of of about 120°, and so here it seems to have been the intersection of straight rather than arcuate fractures that allowed the granite ring to widen. The elongate raft of country rock is situated in this corner.

(v) Structures of the Smaller Intrusions

The boundaries of the O'Connor's Hill and Stony Ck bodies are irregular, and do not seem to have been governed by any pre-existing directions of fracturing in

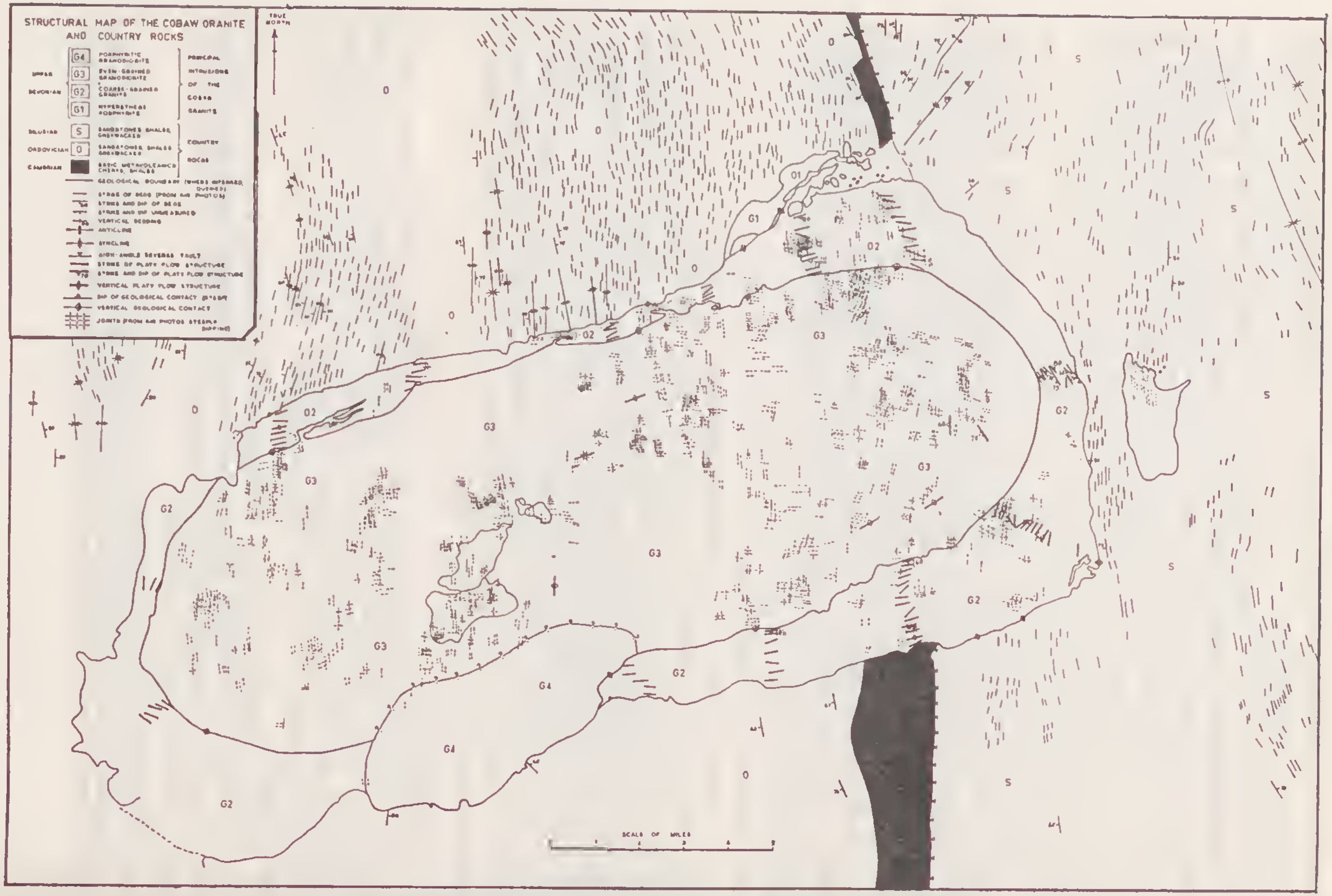

STRUCTURAL MAP OF THE COBAW GRANITE AND COUNTRY ROCKS
UPPER DEVONIAN
G4 PORPHYRITIC GRANODIORITE
G3 EVEN-GRAINED GRANODIORITE
G2 COARSE-GRAINED GRANITE
G1 HYPERSTHENE PORPHYRITE
PRINCIPAL INTRUSIONS OF THE COBAW GRANITE
SILURIAN S SANDSTONES, SHALES, GREYWACKES
ORDOVICIAN O SANDSTONES, SHALES, GREYWACKES
CAMBRIAN BASIC METAVOLCANICS, CHERTS, SHALES
COUNTRY ROCKS
GEOLOGICAL BOUNDARY (WHERE INFERRED, DOTTED)
STRIKE OF BEDS (FROM AIR PHOTOS)
STRIKE AND DIP OF BEDS
STRIKE AND DIP UNMEASURED
VERTICAL BEDDING
ANTICLINE
SYNCLINE
HIGH-ANGLE REVERSE FAULT
STRIKE OF PLATY FLOW STRUCTURE
STRIKE AND DIP OF PLATY FLOW STRUCTURE
VERTICAL PLATY FLOW STRUCTURE
DIP OF GEOLOGICAL CONTACT
VERTICAL GEOLOGICAL CONTACT
JOINTS (FROM AIR PHOTOS) STEEPLY DIPPING
TRUE NORTH
SCALE OF MILES
O
S
O1
O2
G1
G2
G3
G4

Fig. 8—Structural map of the Cobaw Granite and country rocks.

G3. However, the contact of G4 with the country rock is arcuate in trend, and the arc is of a similar size to those forming the boundary of G2 (Fig. 7). The porphyritic microgranite between Pyalong and Glenaroua is separate from the main massif, and is rectangular in plan. Its crenulate and aplitic northern edge is high up the side of a hill, so this may be near the roof of the intrusion. No information on the attitudes of its contacts is available.

(vi) FLOW STRUCTURES

There are no primary flow structures in any of the smaller intrusions (i.e. the granodiorites of the Cobaw Ranges, O'Connor's Hill, and Stony Ck), and the granodiorite G3 is likewise virtually massive. Only seven localities in G3 showed any planar structure (Fig. 8); at four localities the long axes of xenoliths showed parallel orientation, and at three others there were very thin and faint schlieren of biotite. These structures, and the concentric courses of Mollison's and Sandy Ck (see above) suggest the existence of a faint concentric planar orientation in the eastern part of G3, around the adamellite phase.

Singleton (1949, p. 93) observed that the granite of the ring (G2) was 'characterized by the presence of tabular orthoclase perthite crystals, which are oriented in vertical flow layers, parallel to the boundaries of the ring intrusion'. This structure, though not everywhere clearly visible (especially on weathered surfaces) is nevertheless present right around the outcrop of the granite, and is particularly well shown in the creek ¾ mile E. of Sugarloaf Hill, Sidonia (Pl. 34, fig. 2), and in Mollison's Ck, Pyalong.

Inspection of several rock faces at angles to each other in an area of good exposure (e.g. Mollison's Ck) shows that the average parallelism of the perthites is planar. The perthite crystals and biotite flakes are fairly randomly distributed through the rock, though there is a tendency for some of the biotites to be concentrated along the sides of perthite crystals. However, there is no mineral banding (schlieren) or segregation of light minerals from dark, so the term 'foliation', in the sense of Balk (1937, p. 15), cannot be used. Similarly, the term 'flow layers' should not be applied; the flow structure exhibited by the granite is a platy parallelism of phenocrysts.

The attitude of the planar structure is shown principally by the alignment of the largest faces of the tablet-shaped perthite crystals. On the average these faces are vertical, and their strike is parallel to the margins of the granite ring. The smallest faces are therefore horizontal, and the medium-sized faces vertical, but at right angles to the largest faces. The edges of these medium-sized faces should produce a vertical lineation, but the difference in size of the two smaller faces is so slight that this lineation is practically never developed, and it was seen in only two places, in Mollison's Ck.

A platy orientation of the biotite crystals is well shown in only a few places. Here the (001) faces of the larger flakes lie parallel to the overall vertical planar orientation of the perthite phenocrysts. Elongate clots of intergrown biotite flakes are also aligned in the same vertical direction of the planar structure, though the individual flakes of each clot may have any orientation. In a few localities, biotite flakes form vertical strings. However, small isolated flakes generally show no preferred orientation.

The xenoliths in the granite are almost all tabular or lenticular, and their long axes are parallel to the planar orientation.

To determine the attitude of the planar orientation, thirteen traverses were made across the granite ring, and the results are shown in Fig. 8. The attitude of the planar structure proved difficult to determine, for though the strike could be seen fairly readily, the dip was not so easily observed. The general weakness of the planar orientation necessitates good exposures to see it, but these are rarely available, particularly large clean vertical faces. In the only traverse with good vertical exposures (in Mollison's Ck) it was found that even in the one vertical rock face the dip of the planar orientation commonly varied from 10° to 15° on either side of the vertical, indicating the existence of flexures and 'eddies' in the flow layers, so that a single reading could not be taken as indicative of the dip over a large area. However, the measurement of a dozen or so dips at any one locality was not possible, owing to the lack of exposure. For these reasons, only those dip readings that were measured on large surfaces that showed a strong and reasonably constant orientation of the perthites are included in Fig. 8. From this it can be seen that the strike of the planar orientation maintains an average parallelism to the outer contact of the granite ring, and where visible the dip is steep or vertical. This planar orientation is therefore regarded as a platy flow structure, in the sense of Balk (1937), and indicates a vertical flow of magma. There was no tendency for the intensity of development of the platy flow structure to decrease inwards from the outer contact of the granite. This indicates that at this level of erosion, the granite flowed vertically as a true ring dyke between two confining walls, and was not a continuous mass through the region now occupied by the granodiorite G3.

(vii) Joints

These show clearly on the air photographs, and so were plotted directly (Fig. 8). It is clear that there are two main directions of jointing, one approximately N.-S., the other approximately E.-W. These directions are parallel to the long and short axes of the massif. The joints in the granite (G2) show little tendency to form a radial arrangement in the corners of the ring, and the joints in the granodiorite (G3) also seem to ignore the circular nature of the N.-S. contacts of the two rock-types. Joints which cut through the contacts of the two rocks are undeviated. It thus appears that jointing was unrelated to pre-existing structures (such as planar orientation) in the granitic bodies, although the process was undoubtedly influenced by the overall shape of the massif. This suggests that the joints formed after all the members of the massif had been emplaced, except for the final aplite and microgranodiorite dykes. This is supported by the irregularly curved outlines of the granodiorite bodies of Stony Ck and O'Connor's Hill. It is noteworthy that all the final aplite and microgranodiorite dykes strike N.-S. Mineral veneers along joint planes were nowhere seen.

Mode of Emplacement

1. Evidence of Magmatic Flow

The originally fluid nature of the members of the Cobaw Granite Massif have been clearly indicated in the descriptions of the rock units in the section dealing with the petrography and relationships of rock units. The main facts are:

(i) The existence of razor sharp contacts between the outer granite (G2) and the sedimentary country rocks, and between the later members of the complex and the earlier. The younger rocks cut off structures in the older rocks (e.g. platy flow structure).

(ii) The existence of weak platy flow structures, particularly in the ring of granite, G2. The strike of the platy flow throughout the ring is consistently parallel to the outer contact with the country rock (Fig. 8).

(iii) The existence of dykes of granodiorite (G3) which intrude the granite (G2) at Sidonia and NE. of Baynton.

(iv) The existence of dykes of microgranite and microgranodiorite, similar in texture to extrusive rocks. At least two microgranites carry phenocrysts of high-temperature quartz (see above, and Table 2, Pt 4).

2. Conditions in the Crust

(i) A high crustal level of emplacement.

The Cobaw Granite possesses all the more important characteristics of epizonal granites, e.g. those listed in Buddington (1959, p. 677-680). Hence, it is a typical 'high-level' disharmonious pluton, which was emplaced into the upper part of the crust from lower down.

(ii) Absence of compression in the crust during emplacement.

This is indicated by the absence in the country rocks of any distortion which can be attributed to the emplacement of the massif. In Fig. 8, the trend-lines of the Lower Palaeozoic sediments have been plotted from air photographs. They are completely unaffected by the Cobaw Granite, and meet the contact at right angles, where they are abruptly cut off. Structures such as small-scale cross-bedding have been found undamaged within a few feet of the contact. The rocks of the contact aureole possess typical hornfels texture (see section on petrography above), which indicates absence of stress (Pitcher & Read 1963). The belt of Cambrian rocks is cut through by the granite, but on either side of the massif its N.-S. trend is maintained (Fig. 1b). The weakness of the flow structures also indicates little or no pressure on the magmas during emplacement.

Workers in other areas of 'high-level' granites have concluded that ring dykes and collapse structures came about while the crust was either in a neutral state (Billings 1943, 1945) or a tensional state (Richey 1932, Oen 1960); certainly there was no horizontal compression acting in the crust during the emplacement.

(iii) Pre-existing fractures in the country rocks.

The existence of these is indicated by the parallel trends of the two E.-W. contacts, and the two arcuate N.-S. contacts of the Cobaw Granite massif. Moreover, the E.-W. contacts are composed of several very broad arcs (Fig. 7), and the overall strike of these arcs has the same general E.-W. direction. It is noticeable that these E.-W. boundaries can be produced to coincide with similar straight boundaries of the neighbouring Strathbogies Granite to the E. (Fig. 1b). This may reflect the existence of faults or fractures in the basement beneath the Palaeozoic sediments of the geosyncline (cf. Williams 1964, p. 313).

Secondly, the Cobaw Granite is centrally situated in the Riddell Trough, and shows complete discordance with it; the long axis and the major (E.-W.) contacts of the massif are at right angles to the long axis of the trough (Fig. 6). In this part of the Central Victorian region, the brachyanticlinoria and synclinoria have a N.-S. strike (as do most of the individual folds), and so the direction of major lines of weakness might be expected to have an E.-W. trend, a relation analogous to that shown by the cross-faults which form at right angles to the axes of folds.

The arcuate nature of the boundaries (and hence of the pre-existing fractures in the country rock) indicates that in these areas at least, the lateral forces in the crust at the time of formation of the fractures were equal and invariable (de Sitter 1956, p. 251). The existence of straight boundaries as well results from the structure of the country rocks—i.e. the prevailing N.-S. trend of the folds.

The fractures (or fracture zones) which governed the form and emplacement of the Victorian granites were not the faults in the country rocks which formed during the Tabberabberan Orogeny, at the end of the Middle Devonian. These faults, such as the Muckleford, Whitelaw, Mt William, and Heathcote Faults, are completely transected by the granites (Fig. 6). Accordingly, the fractures used by the granites were generated after the Tabberabberan Orogeny.

SUMMARY OF CONDITIONS BEFORE AND DURING THE EMPLACEMENT OF THE COBAW GRANITE

(i) The original granitic materials were magmas.

(ii) Emplacement took place in the upper part of the earth's crust.

(iii) The crust was not under compression, and was probably under slight lateral tension. The lateral forces were mostly equal and invariable.

(iv) The crust was cut into segments by fractures and fracture zones, which were straight or arcuate in plan, and mainly vertical in depth.

3. THE ARGUMENT FOR SUBAERIAL EMPLACEMENT RATHER THAN SUBSURFACE EMPLACEMENT

There is no evidence in the area which settles this question, as all rocks older than the intrusives and within the boundary of the massif have either been displaced by the intrusives themselves, or have been eroded away. The complete absence of volcanics associated with the Cobaw Granite at first suggests subsurface emplacement of the massif. However, in the other Victorian complexes that do have volcanic rocks preserved, the extrusion of these rocks was accompanied by central collapse —i.e. the vertical subsidence was greatest in the middle of the cauldron (as in the Ossipee Mountains of the U.S.A.; Kingsley 1931). Considerable thicknesses of volcanic rocks were formed, e.g. 6,000 ft in the Cerberean cauldron (Hills 1959, p. 548), and it is the downfaulting or warping that has resulted in the preservation of these volcanics to the present day. If the emplacement of the intrusions of the Cobaw Granite were preceded by acid vulcanism, the volcanic rocks have since been entirely removed by erosion. This suggests that the volcanics were originally present in smaller amount, and as a much thinner layer, than the volcanic piles of the other areas, and this implies that little or no collapse occurred, and especially not central collapse.

However, it is not essential for subaerial cauldron subsidence to be always accompanied by central collapse. In many of the ring complexes of the Younger Granite Province of Nigeria (Jacobson, Macleod, & Black 1958), and also in those of Queensland (Branch 1962), the volcanics of the cauldrons are flat-lying, except where local upturning at the edges took place owing to drag during the subsidence. The circumstances of the Cobaw Granite and its neighbouring volcanic massifs are similar to those in the NW. part of the Nigerian area, where the Kudaru complex has no volcanics, and the Banke and Liruei complexes, 10 miles away to the north and north-east, have plenty of volcanics preserved. Jacobson (pers. comm.) feels that the Kudaru complex very probably did have an early extrusive phase, and that the volcanics have since been completely removed, owing to uplift of the Kudaru complex relative to the others by later block faulting.

It is possible, therefore, that the Cobaw Granite did have a volcanic phase, that the acid lavas were thin and restricted, and that they have long since been removed by erosion. It is clear that, since the Upper Devonian, a good deal of denudation has taken place in Central Victoria, for large areas of Lower Ordovician rocks are now exposed, and Silurian and Lower Devonian rocks are completely absent W. of the Mt William-Heathcote-Colbinabbin Belt.

From the large size of the Cobaw Granite (24 by 8 miles), it is very likely that the initial bounding ring fractures, which formed close to the present position of the granite-country rock contact, extended to the surface. The volcanics could then have been extruded from these, and so constitute the earliest igneous activity. The phenomenon that the earliest igneous phase in ring complexes is a volcanic one has been found in many parts of the world, and Central Victoria is no exception (Hills 1959). Indeed, it seems to me that the first ring fractures could only be prevented from reaching the surface by a large horizontal fracture that had formed even earlier. There seems no reason why this fracture should form at that stage, except perhaps by magma withdrawal. This would require connections (probably horizontal) between magma chambers, and a reason for their existence is hard to find. Rather, it is more likely that horizontal fractures would form later, inside the initial ring fractures, and so segment the large block of crust that had been isolated by the first fractures.

4. The Argument for Block Subsidence rather than Block Uplift

Again, there is no direct evidence either way, such as fragmentation of roof rocks by doming (cf. Smith, Bailey, & Ross 1961), or downwarping of volcanics. However, a decision for block subsidence can be reached on indirect lines.

Granitic magma has a density of about 2·4 (Iddings 1914, p. 98; Daly 1933, p. 46-49, 57; Shaw 1965, p. 128), and so it is less dense than a consolidated geosynclinal filling of folded greenstones, greywackes, sandstones, and shales, which has an overall density of 2·7 to 2·8 (Grout 1932, p. 157; Daly 1933, p. 248; Holmes 1944, p. 478). This figure of 2·7 to 2·8 is supported by the fact that the basic vulcanism of late Tertiary times in Central and Western Victoria took the form of copious outpourings of lava, with a density of about 2·7 (Holmes 1944, p. 479), not intrusion of dolerite sills and cone sheets, so that the crust must have been denser than the basalt magma; cf. Carey (1958).

It is most likely, therefore, that once movements of blocks of country rock started, these blocks sank rather than rose. The Cobaw Granite is regarded, therefore, as having been emplaced by block subsidence.

5. Formation of Steeply-dipping Fractures

As discussed above, these formed in response to the lateral tension induced in the crust by the upthrust of the lighter granitic magma in the magma chamber. Some were straight (in plan), where governed by pre-existing weaknesses in the crust, derived from the N.-S. 'grain' in the country rocks. Others were arcuate, where pre-existing weaknesses were subordinate. The arcuate fractures particularly provide support for slight doming, as they indicate that inequalities in the forces in the same lateral plane were small, and this is an inherent property of doming.

The attitude of the fractures was steeply-dipping or vertical, in response to the approximately horizontal forces of tension, and the fractures probably maintained this dip throughout their whole vertical extent. A constant dip is not found in the well-known diagram in E. M. Anderson's analysis, where the ring dykes were thought to have formed by oblique shear along a surface which lay at an angle to concentric paraboloidal surfaces of tension (Anderson 1936, p. 151), these surfaces being approximately parallel to the top of the magma chamber. Accordingly, the dip of the ring dykes would be expected to diminish towards the top, a characteristic not commonly found in actual occurrences. However, Jeffreys (1936, p. 162) pointed out that once the ring fracture formed at the top of the magma chamber, it would far more likely maintain its original attitude as it extended upwards, so that a more nearly cylindrical fracture would result. Again, de Sitter (1956, p. 105) holds that oblique shear is rare in naturally deformed rocks. Anderson's theory was put forward before the large size of many ring dykes was known, and it explained the origin of ring dykes in terms of fluctuations of pressure in a fairly small magma chamber, ascribing a far more active role to the magma directly below the site of the ring dyke. In the present hypothesis, it is felt that the ring dykes are the result of a certain arrangement of fractures in the roof of the magma chamber, and that these existed before vertical movements or pressure differences in the magma began.

6. THE NATURE OF FRACTURE ZONES

Before describing the sequence of events in the Cobaw Granite, it is necessary to discuss the term 'fracture zone', already used several times. Fracture zones are postulated (1) in order to form a complete ring dyke before movement of any central block of country rock occurs, and (2) to allow subsidence of this block when its bounding fractures are vertical or inward-dipping. Where the walls of a block of country rock are outward-dipping, subsidence is unrestricted and magma emplacement can take place by simple permissive intrusion into the opening fissure. However, where the walls are vertical or inward-dipping, subsidence does not open a fissure.

To solve this problem, Billings (1943, where he also gave full credit to the earlier development of essentially the same idea by Richey 1932, p. 99, 132) suggested the 'fracture zone', composed of a number of straight or arcuate fractures arranged in a zone, and perhaps bounded by larger fractures (Fig. 9b). The magma could first stope out this zone on either the piecemeal or minor block stoping scale (the blocks in the latter case are from ¼ to ½ mile across), and so form a ring dyke around the central block of country rock, which need not yet have moved. This would clear a region around the central block, and also remove the support provided by the walls. Eventually the central block could break free of the roof and subside into the magma.

In relation to this concept of the fracture zone, it is worth noting that Clough, Maufe, & Bailey (1909, p. 665) in their description of the classic Glen Coe Cauldron-Subsidence, concluded that the 'fault intrusion', which was intruded around the outside of the Glen Coe ring fault at the same time as the main subsidence took place, and can be considered an incomplete ring dyke, was emplaced by piecemeal stoping, and they also thought that the magma may have reached the surface (idem. p. 666-667).

Fracture zones have been invoked by Jacobson, Macleod, & Black (1958, p. 9, 33, 69) to explain the emplacement of the ring dykes around some of the Nigerian ring complexes, and something of the sort probably occurred in the emplacement of the Cobaw Granite, for the walls are certainly very steeply-dipping, and parts of the attitude of the platy flow structure suggest an inward dip (Fig. 8).

SEQUENCE OF EVENTS IN THE EMPLACEMENT OF THE COBAW GRANITE

INTRODUCTION

The process of intrusion seems to be broadly this:

A body of granitic magma becomes positioned in the crust, and because of its lower density, tries to rise. Slight doming of the roof ensues, and the resulting tension is relieved by the formation of the first ring (or polygonal) fractures and fracture zones. These reach right to the surface, and some of the magma moves up them, enlarging the channels by minor block stoping. Extrusion of acid volcanics results, in greater or lesser amount, depending on such factors as the supply of magma, its temperature, composition, density, hydrostatic head, amount of contained volatiles, etc.

The block bounded by these initial ring fractures is now resting upon and tending to sink into the remaining magma below, which itself is still trying to rise. The resulting stresses are released by more fracturing, and these fractures would probably have a strong tendency to form within the block enclosed by the initial ring fractures, because the blocks enclosed by these later fractures would be so much smaller, and therefore more easily displaced by the magma. This is why the later activity in ring complexes is so commonly confined within the earliest ring fractures, another pattern shown throughout the world, and by the Cobaw Granite. Sinking of these smaller blocks allows the upwelling of the rest of the magma, to give the later intrusions of the complex inside the earlier.

1. Preliminary Minor Intrusions

The intrusive sequence began with the intrusion of the hypersthene porphyrite dyke G1, at Tooborac. Although the dyke is irregular in plan, its overall trend is arcuate, and the intrusion was probably accomplished by stoping of an arcuate fracture zone (Fig. 9a). The dip of the dyke is not known, but is probably steep. The dyke probably reached the surface and extruded some hypersthene dacite; if so this has been removed by erosion, and must have been a small flow.

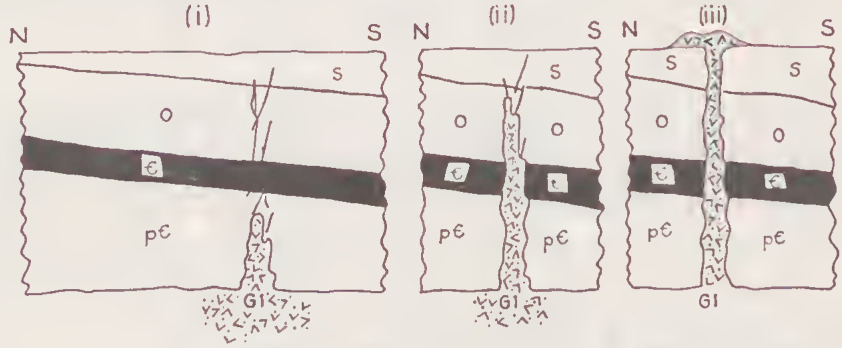
After consolidation of the hypersthene porphyrite, the small irregular dyke of microgranodiorite at Tooborac, the porphyritic microgranodiorite dyke at Mt William, and the porphyritic microgranite SE. of Tooborac were intruded. The dyke at Mt William came in by simple injection of magma into a parallel-sided fissure which opened in the greenstone. The body at Tooborac contains few xenoliths, in spite of its irregular shape; perhaps it was emplaced by stoping of several blocks, as in the case of the hypersthene porphyrite.

2. Granite G2

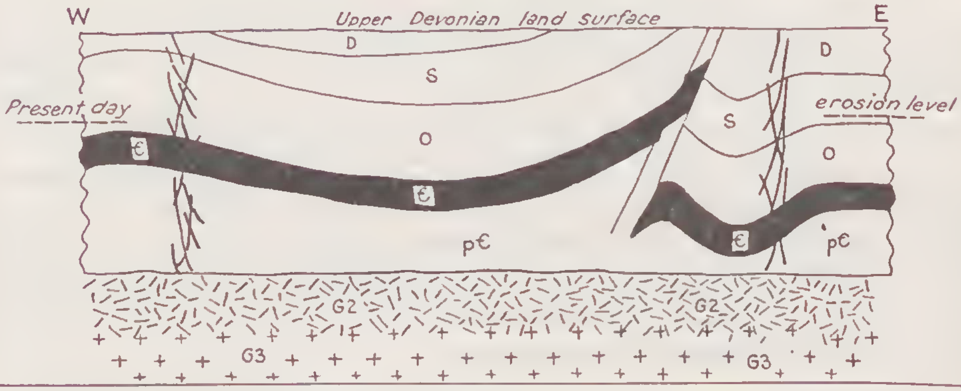
After these preliminary intrusions came the uprise of the magma to form a complete 360° ring dyke of granite G2. The precise attitude of the outer contact of this ring intrusion is uncertain, but it is very steep, and probably varies from steeply outward to steeply inward-dipping. It is necessary, therefore, to intrude the granite by minor block stoping of a ring fracture zone, Fig. 9b, 9c. This stoped out a region right around the central block of country rock, and resulted in the emplacement of the ring dyke of granite and restricted flows of rhyolite (Fig. 9d, 9e). These must have been thin, and it is unlikely that very much subsidence took place. Several rhyolite volcanoes may once have existed, positioned above the ring fracture zone. The ring fracture zone was subrectangular in shape, and had approximately straight and parallel E.-W. sections and arcuate N.-S. sections. However, there were additional fractures outside the main trend of fracturing at three of the four corners. In two of these, the SW. and NE. corners, the extra fractures were arcuate, but in the SE. corner the fractures were straight.

Evidence of the minor block stoping by the granite G2 can be seen at a number of places. At Tooborac, the medium-grained granite dyke, which intrudes the country rock parallel to the main contact, shows the actual stoping in progress, the

a. Intrusion of hypersthene porphyrite, G1; forms small flow of hypersthene dacite.



b. Formation of steeply-dipping ring fracture zone.



c. Start of intrusion of coarse-grained granite, G2, by minor block stoping of ring fracture zone.

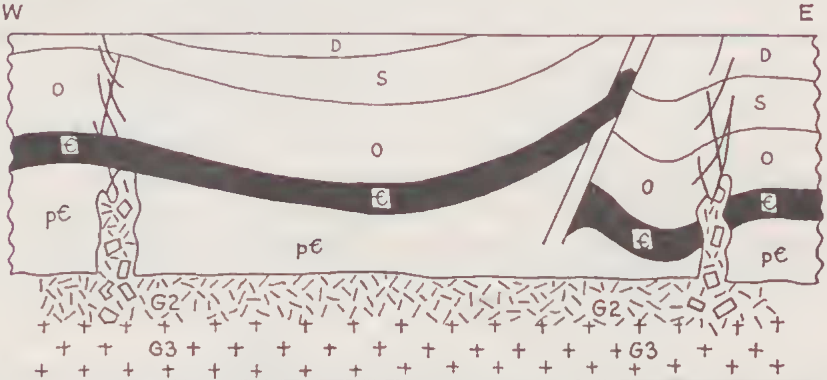
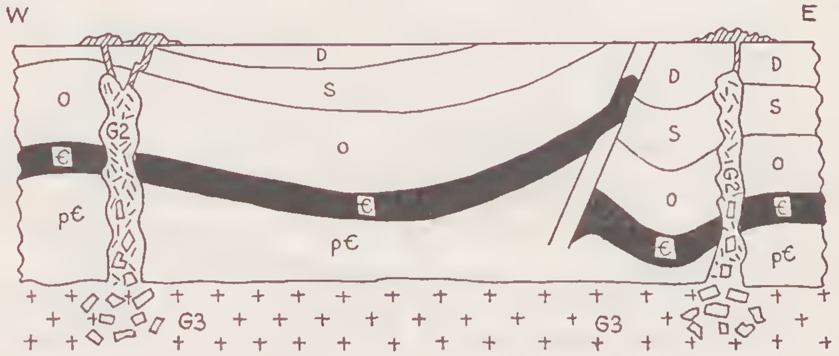
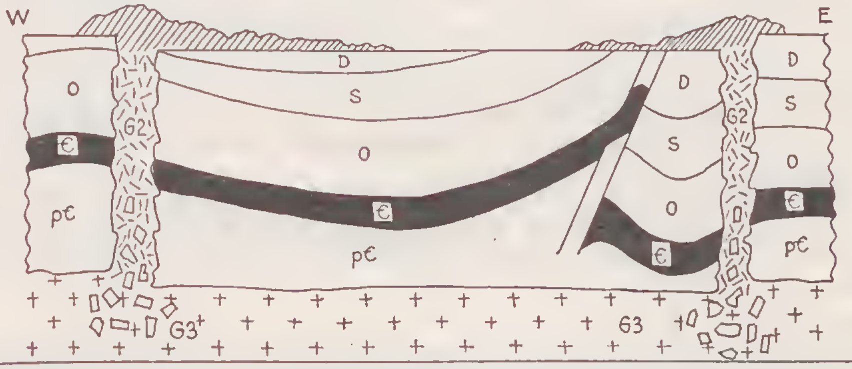


FIG. 9. a ,b, and c—Initial events in the emplacement of the Cobaw Granite. (a) irruption of G1, (b) formation of ring fracture zone, and (c) minor block stoping of this to intrude G2. Vertical and horizontal scales are equal, approximately 8 miles to 1″. Reference as for Fig. 2, except that all Cambrian rocks are shown in solid black, and those labelled pЄ and D are hypothetical Precambrian and Devonian rocks respectively.

d. Intrusion of granite, G2; magma reaches surface.



e. End of intrusion of granite, G2; rather more magma reaches surface to give restricted flows of rhyolite, and central block of country rock collapses a short distance.



f. Formation of horizontal cross-fracture and possible N/S vertical fracture in central block of country rock, and steep ring fracture in solidified ring of granite, G2.

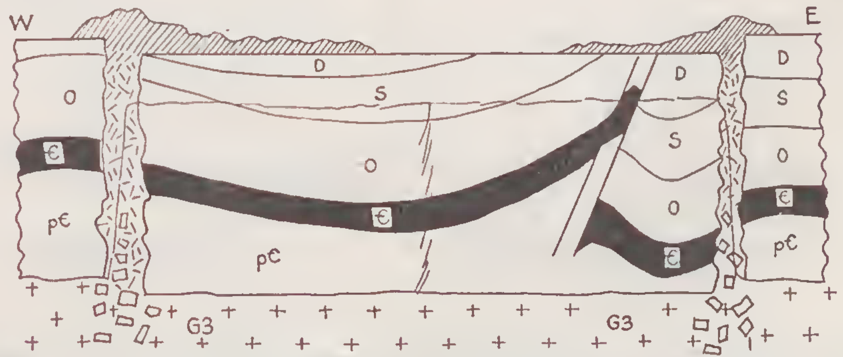


Fig. 9. d, e, and f—Succeeding events in the emplacement of the Cobaw Granite. (d) intrusion of G2, (e) extrusion of restricted flows of rhyolite, and (f) formation of subsurface fractures.

magma prising loose a slab of wall rock but solidifying before the slab was finally freed. At High Camp, in the SE. corner, there is a large partly or wholly stoped block of country rock in the granite. Elsewhere, the entire contact of the granite with the country rocks shows irregularities which suggest that blocks have been stoped away. The general rarity of xenoliths and rafts is admittedly discomforting, and I can only assume that they sank out of sight into the depths (cf. Steven 1957, p. 369, and Oen 1960, p. 283). Shaw (1965, p. 129) gives some support for this in a quantitative treatment of viscosity in granite magmas. The same problem is encountered with the ring dykes of the Sara-Fier complex of the Nigerian Younger Granite Province (Turner 1963, p. 361). Even here a few large blocks of country rock have been found in the granites, suggesting that 'large-scale stoping' operated (idem, p. 353).

The slow upward irruption of the granite magma, composed of a mush of perthite phenocrysts, oligoclase crystals, biotite flakes, and residual liquid, took place by approximately stream-line flow, though some turbulence was present in places, probably owing to the presence of stoped blocks, and of 'lumps' in the magma which contained more solid and less liquid than the surrounding material. The 'stream-lines' were actually two-dimensional 'stream-planes', which were oriented parallel to the boundaries of the ring. The tablet-shaped perthite and biotite crystals were then dragged into parallelism to these planes, and the weak platy flow structure in the granite resulted. The poor development can be explained by the low pressure on the magma owing to the absence of compression in the crust, and by the high proportion of solid material in the mush, so that it only slowly welled upwards, like 'thin lumpy porridge'. The magma cooled and solidified, and this was followed by injection into the jointed country rocks of dykes of porphyritic microgranite.

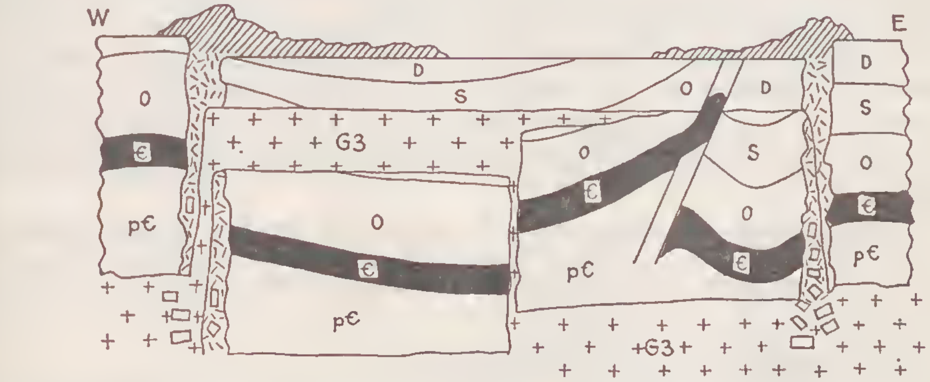
Probably about the same time as the emplacement of the granite ring dyke, an off-shoot of granite formed the porphyritic microgranite between Pyalong and Glenaroua. It too is nearly devoid of xenoliths, and its mechanism of intrusion is unknown.

3. GRANODIORITE G3

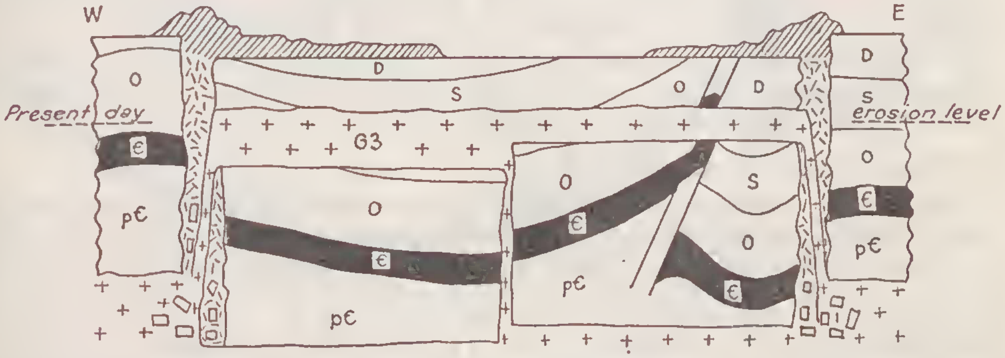
Following the emplacement of the ring of granite G2, there remained below a large body of granodiorite magma. A horizontal cross-fracture or zone of fractures formed in the central block of country rock, owing to the tendency of the block to sink into this granodiorite magma (Fig. 9f). The level of the horizontal fracture (or zone) with respect to the ring of granite is not known, but it was probably in the upper part of the block. The formation of this cross-fracture must have been accompanied by the formation of a steep-sided ring fracture which was situated entirely within the solidified (but unjointed) ring dyke of granite G2. This is indicated by the absence of any screens of country rock between the granite and granodiorite, and by the overall regularity of the contact of these two rocks. Subsurface cauldron subsidence took place within these fractures to allow the intrusion of the granodiorite G3 inside the ring of granite G2 (Fig. 9g).

The details of this collapse are not clear—i.e. whether subsidence of one great block took place, or of a few large blocks, or of many smaller blocks. The remarkably even shape of the granodiorite outcrop strongly suggests that only one or a very few blocks were involved in the collapse, and the indications of a weak concentric planar orientation in the eastern half of the granodiorite (Fig. 8) suggest that the collapse may have taken place by subsidence of two blocks of roughly the same size (Fig. 9h).

g. Intrusion of granodiorite, G3, starting in western part of massif by subsidence of block of country rock.



h. End of intrusion of granodiorite, G3, by subsidence of eastern block of country rock.



i. Intrusion of porphyritic granodiorite, G4. (i), Formation of arcuate fracture in country rock; (ii) subsidence of block of granite plus country rock, and uprise of G4 magma to mingle with the still liquid G3.

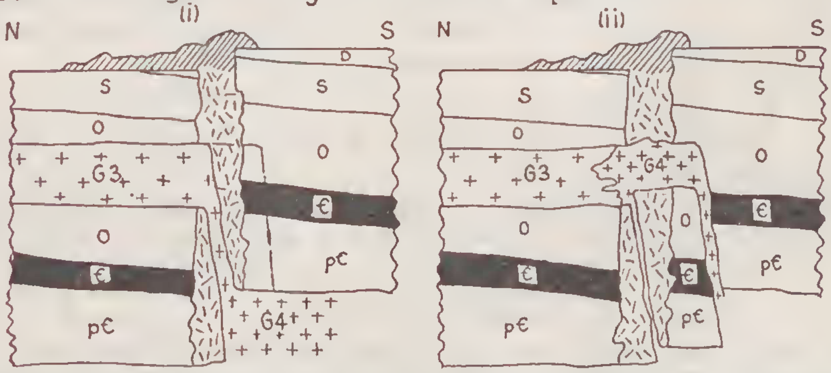


Fig. 9. g, h, and i—Conclusion of main events in the emplacement of the Cobaw Granite. (g) start of intrusion of G3, (h) completion of intrusion of G3, and (i) intrusion of G4.

The evidence for piecemeal stoping provided by (a) the concentration of the hornblende-bearing xenoliths in a zone which follows the strike of the Cambrian belt, and (b) the indications of a sedimentary origin for the non-hornblende-bearing xenoliths, indicates that the granodiorite had free access to the country rocks above the cross-fracture. The granodiorite also stoped the granite on the minor block scale to some extent, and this resulted in the small irregularities in the contact. However, the overall evenness of the contact indicates that this marginal stoping cannot have been much. As with the medium-grained granite dyke at Tooborac, the forked granodiorite dyke at Sidonia shows the granodiorite stoping out some blocks of granite.

The granodiorite cut cleanly across the platy flow structure in the granite, so that complete solidity of the granite in the ring dyke before the intrusion of the granodiorite is indicated. The granodiorite in places became slightly porphyritic at the contact.

4. GRANODIORITE OF THE COBAW RANGES G4

Immediately following the intrusion of G3 came the emplacement of the granodiorite G4. This was managed by subsidence of a block made of portions of sedimentary country rock and granite G2, along an arcuate fracture in the country rock which lay outside the boundary of G2 (Fig. 9i). G4 has a sharp contact with the sediments, but a transitional contact zone with G3, so that the latter was still partly fluid during the intrusion of G4. Stoping of the roof was negligible, but a few xenoliths of granite (G2) are present.

5. LATER MINOR INTRUSIONS

Two, and possibly three small bodies of granodiorite followed the emplacement of G4. One formed the dyke of porphyritic microgranodiorite N. of Baynton, which was injected into the ring of granite G2, perhaps contemporaneously with the emplacement of G3. A much larger mass of porphyritic microgranodiorite formed the intrusion at O'Connor's Hill near the middle of G3, and this caused some recrystallization of the surrounding rock. A small off-shoot of this intrusion came in to the north-east. The porphyritic texture of these intrusions, and of the microgranite between Pyalong and Glenaroua, resulted from their small size and the consequent more rapid cooling than in the larger, earlier masses. The mechanism of intrusion of the O'Connor's Hill body is unknown, but it was probably subsidence of large blocks of granodiorite (G3) accompanied by small-scale stoping. Several rafts of G3 in the microgranodiorite support this.

After these intrusions came the porphyritic granodiorite of Stony Ck. Four plugs of this granodiorite were injected at points around the contact of the O'Connor's Hill body, and a fifth off-shoot was emplaced beside the off-shoot from the O'Connor's Hill mass.

Following this, the small plug of coarse-grained granodiorite beside the previous two off-shoots, and the eight minor intrusions around the margin of G4 moved in. The occurrence of these minor bodies in this zone suggests that this was a favoured site of intrusion. Their sharp contacts indicate that G4 had solidified, so they may have been injected along weaknesses and openings in the contact zone, which formed as the mass cooled. They may be the result of the mingling of G4 magma with the unconsolidated granodiorite, G3. The granitic types may represent acid differentiates which formed during the consolidation of the G4 magma, perhaps assisted by minor melting of the granite G2.

The concluding stages saw the injection into early joints of porphyritic microgranodiorite and microdiorite dykes, sheets and dykes of aplite, veins of pegmatite, and rare quartz reefs. These early joints probably formed in response to E.-W. tension in the crust, as almost all the dykes strike N.-S. The dykes and rare pegmatite and quartz veins represent the 'dregs' of the magma, and conclude the emplacement history. Fig. 10 is a block diagram which shows the final configuration of the massif at the present time.

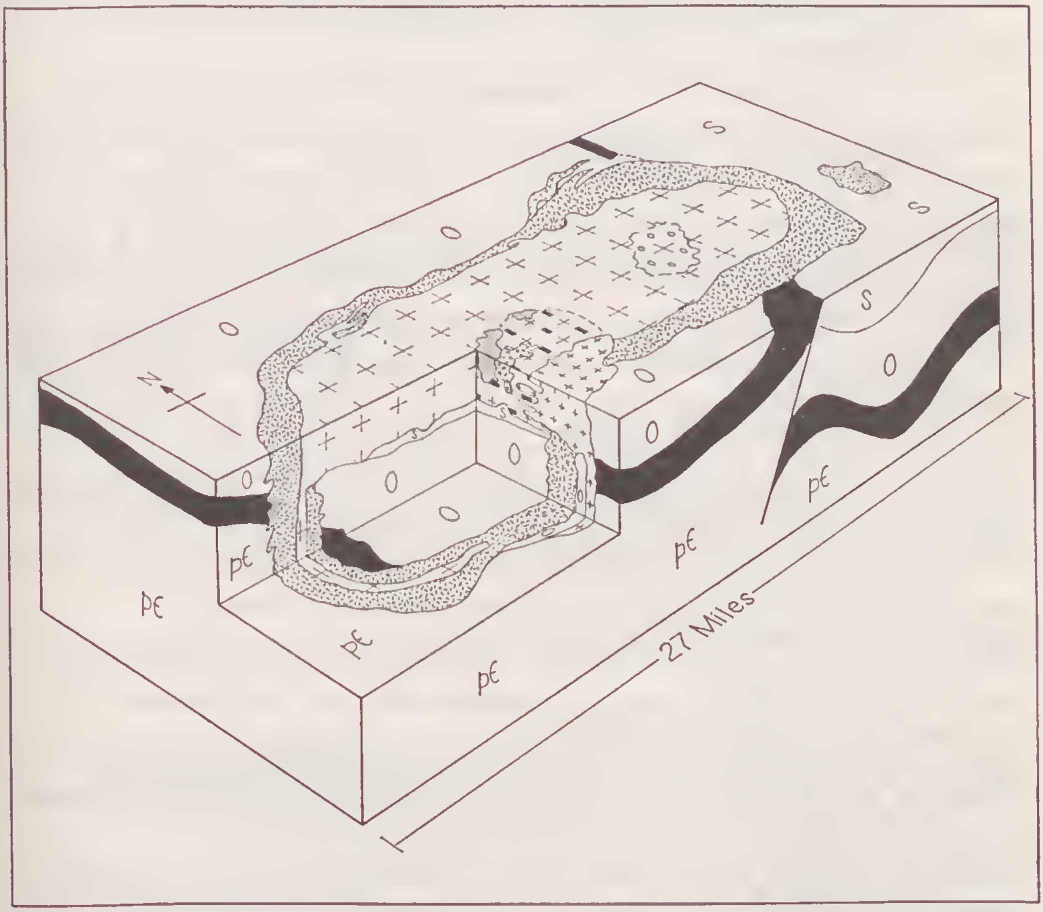


FIG. 10—Block diagram of the Cobaw Granite at the present time, with one corner removed to show part of the subsided block of country rock in the south-western part of the massif. Reference as for Fig. 2, except that all Cambrian rocks are shown in solid black, and those labelled pЄ are the Precambrian basement. Vertical and horizontal scales are equal, approximately 8 miles to 1".

Acknowledgements

This work was done while holding a Research Grant and Howitt Natural History Research Scholarship in the University of Melbourne. I wish to thank Professor E. Sherbon Hills for suggesting and supervising the work, and for allowing the use of the facilities in the Geology Department. Thanks are also due to the staff